AMSAT
RADIO AMATEUR SATELLITE
CORPORATION

PROCEEDINGS OF THE
AMSAT-NA

20th Space Symposium
## and **AMSAT-NA** Annual Meeting

November 7-11
2002
Fort Worth, Texas

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Welcome to Fort Worth!

It is now nine years since AMSAT last held a space symposium and annual meeting in Texas. At that time Keith Pugh, W5IU, was our organizer of the event and if I remember correctly it was one of the more memorable events in AMSAT history.

It is a delight to be back here again albeit slightly 'down the road' from the previous site in Arlington. Keith and his crew are once more our hosts, keeping up the fine service that they started in 1993.

Since last year's meeting in Atlanta, many things have happened which affect AMSAT in a variety of ways, and perhaps now is a good time to review the past 12 months.

Project Eagle is now progressing and we hope to have the design completed by next year. This satellite will fill in several of the missing modes of AO-40 and certainly include Mode B, which has been requested by so many people. Dick Jansson's paper on this satellite will provide more information.

During the past year, we have announced the development of AO-E, usually refered to as "Echo". Echo will be another Microsat in size with functionality of a much larger satellite due to the high efficiency Photocells and the decreasing size of the electronics. Rick Hambly's Paper on Echo gives the details.

Unfortunately, due to 9-11 and the general slowdown of the US economy funds for our projects are arriving more slowly than had been planned to keep 'Eagle" on the 2004 schedule. Reluctantly we have had to reschedule this satellite to 2006, in the hope of being able to meet an estimated $2.6 Million - even this later date looks somewhat optimistic, unless each AMSAT-NA member contributes $100/year to the building fund, are we asking too much?
Another funding campaign will commence this (November) Month.

Once more Welcome to Fort Worth - May you enjoy your weekend.

Robin Haighton VE3FRH
President AMSAT-NA

AMSAT OSCAR-E Project Status Update
A New LEO Satellite from AMSAT-NA
Richard M. Hambly (W2GPS)

This status report about AMSAT-OSCAR-E ("Echo") is an update to the presentation given at the Dayton Hamvention and the articles published in the AMSAT Journal (May/June 2002) and CQ/VHF Summer 2002.

BACKGROUND:

Following the 2001 Annual AMSAT-NA Meeting in Decatur GA, the Board of Directors met and asked Dick Daniels (W4PUJ), Tom Clark (W3IWI) and Rick Hambly (W2GPS) to review a proposal for "a new small satellite project." The team's report was presented to the Board during a teleconference on 17-Jan-02 and the Board unanimously approved the project.

AMSAT-NA built and launched the original Microsats in 1990. These were AO-16, DO-17, WO-18, and LO-19. The descendents of the Microsat legacy include IO-26, AO-27, MO-30, and SO-41. Each of these descendents has improved on the original design. The project team recommended that AMSAT-NA take full advantage of these improvements so, on 8-Feb-02, AMSAT-NA entered into an agreement with SpaceQuest, Ltd. of Fairfax, VA whereby SpaceQuest will provide AMSAT with the basic components of AO-E and leave it to AMSAT members to add any specialized payloads that may be desired. SpaceQuest is led by AMSAT members Dr. Dino Lorenzini (KC4YMG) and Mark Kanawati (N4TPY).

On 20-Apr-02 the AMSAT Board met at SpaceQuest to see firsthand that everything was going as planned. After the tour of SpaceQuest, the Board reconvened across the street in ARRL's DC area offices where there were presentations and an extensive review of the project. It was at this meeting that the Board agreed to postpone the launch
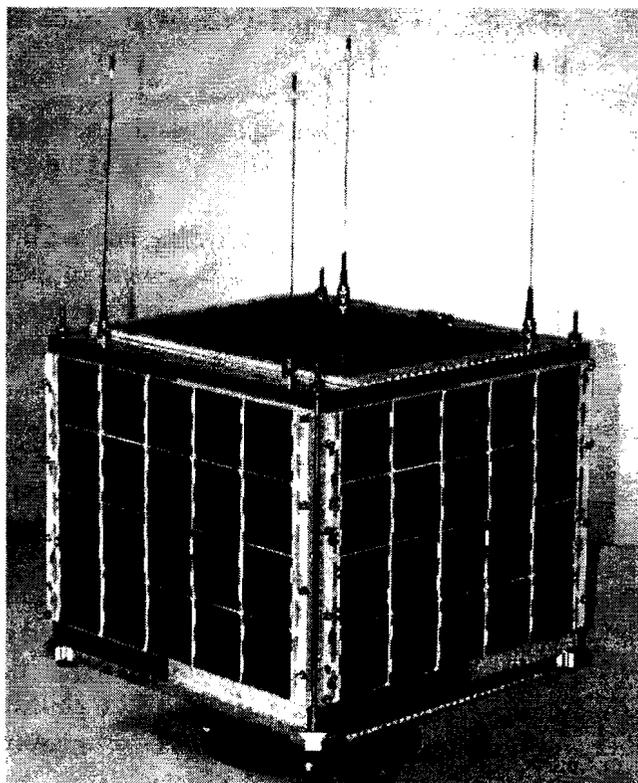
Figure 1 - Mechanical Model of AO-E Class Microsat

until late 2003 to provide adequate time for the development of optional payloads.

The first public presentation on AO-E was at the annual spring AMSAT-DC symposium at NASA Goddard Space Flight Center on 5-May-02. The presentation was significantly compressed for the Dayton Hamvention AMSAT Forum on 18-May-02.

Full details of the project were published in the May/June AMSAT Journal. A reprint of the Journal article has appeared in the Summer 2002 issue of CQ/VHF magazine.

Figure 2 - The AMSAT Board, Project Committee and SpaceQuest personnel at SpaceQuest 20-Apr-02

Throughout the year the AMSAT project team (W4PUJ, W3IWI, and W2GPS) has met on a regular basis with SpaceQuest and others to review the progress of AO-E and to discuss the various optional payloads that are under consideration.

FEATURES

The AMSAT OSCAR-E satellite will offer users a strong set of features even before optional payloads are added. These include:

- Analog operation including FM voice.
- Digital operation including APRS.
- High downlink power.
- Multiple channels using two transmitters.
- Simultaneous voice and data,
- Multi-band, multi-mode receiver.
- Geographically based personalities.

- True circular UHF antenna that maintains its circularity over a wide range of squint angles.

TECHNICAL

AMSAT OSCAR-E will be a step forward in the evolution of Microsat technology, with better receivers, higher power transmitters, and new operating modes.

The infrastructure of the satellite has many improvements over earlier generation Microsats, including:

- Faster and more capable IHU processor.
- Higher data rates on downlinks.
- Autonomous, self-healing, high efficiency power management system.
- Upgraded, highly capable, software package.
- Store and forward with continuous monitoring and geographically defined data forwarding.

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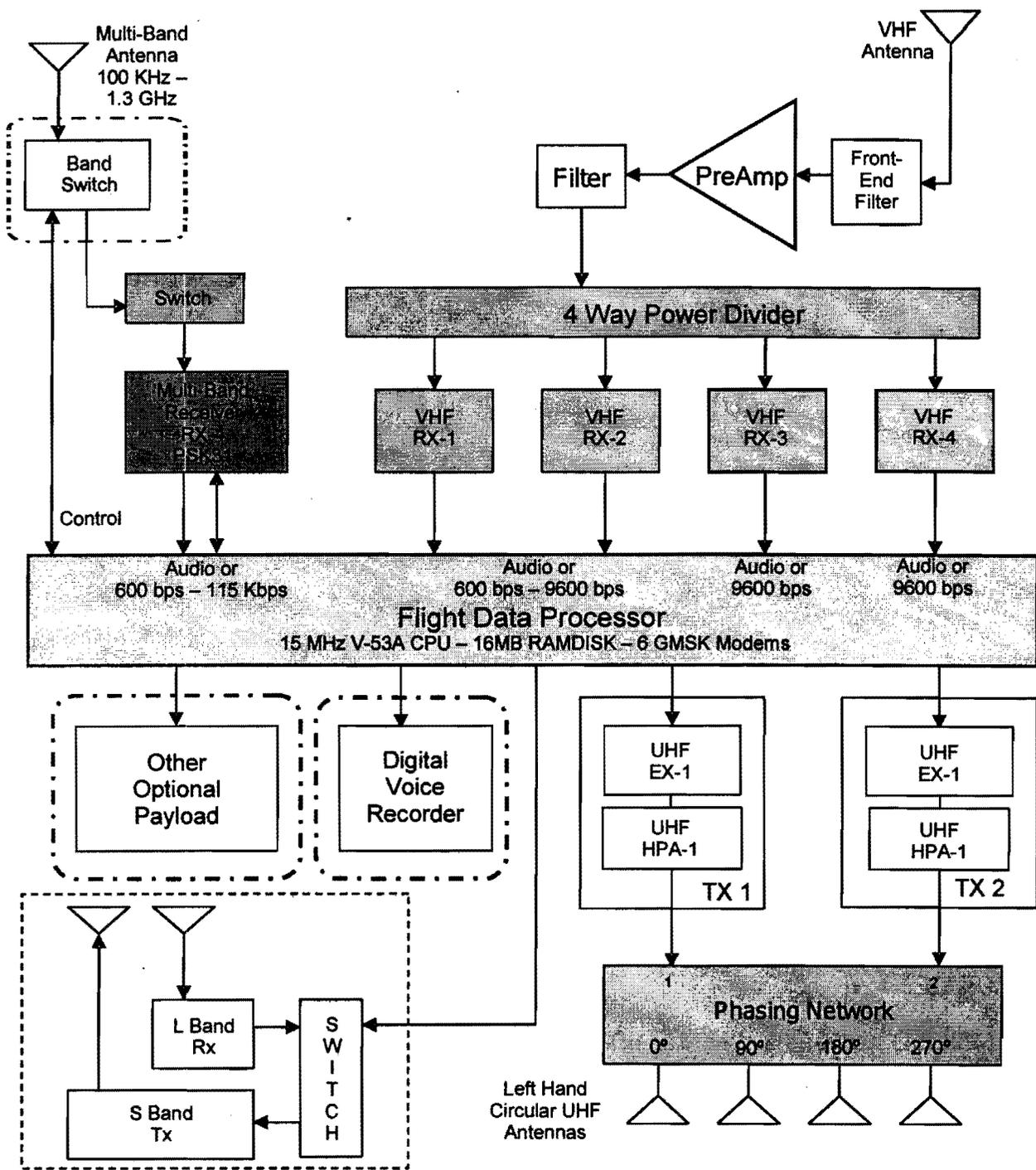
**Figure 3 - Conceptual Block Diagram of the AMSAT OSCAR-E Spacecraft**

The internal subsystems have been described in detail in the AMSAT Journal article (May/June 2002) so only a summary is presented here.

The core elements of the AMSAT OSCAR-E satellite are being provided by SpaceQuest. This provides the basic platform on which AMSAT can build using optional payload trays and external modifications.

The subsystems that make up the core elements of AMSAT OSCAR-E are:

- The physical structure
- Attitude control
- Central processor hardware
- Spacecraft flight software
- Power generation and distribution
- Command and control
- A basic set of receivers, and transmitters
- Antennas.
- Space for optional payloads

Physical Structure

AMSAT OSCAR-E is made up of a stack of five machined aluminum modules each measuring 23.5mm x 23.5mm. The height of the stack is 24.5mm.

One module is empty and is to be used by an AMSAT supplied payload. Internal to the module there is 200mm x 220mm of space with rounded corners. The height is about 50mm.

Figure 4 shows a photo of a typical Microsat structure.

Active Magnetic Attitude Control

Originally an optional payload, the active magnetic attitude control has replaced the passive system as one of the core satellite subsystems. This will allow the spacecraft to be oriented to favor communications in the Northern or Southern Hemispheres at different times.

This attitude control system replaces the permanent rod magnets with semi-permanent electromagnets. Electronic circuits are required to polarize and condition the magnetic rods.

The Earth-pointing direction is on the order of ±20 degrees in the temperate zones, varying with orbital inclination.
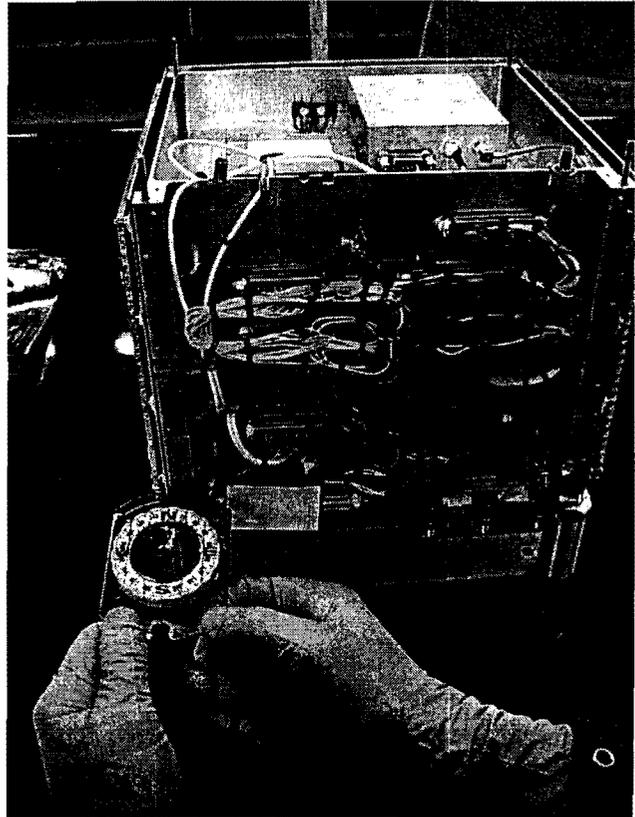
Figure 4 - Typical Microsat Structure

As this is being written Lou McFadin W5DID has the stabilization rods for winding. Doug Sinclair is designing and building the electronics to control magnetization of the rods.

Central Processor Hardware

AMSAT OSCAR-E includes an improved Integrated Flight Computer (IFC) recently developed by Lyle Johnson WA7GXD.

The improved IFC used a new six layer circuit board and includes a flight-proven, low-power NEC V53A processor Central Processor Unit (CPU) that runs at 30MHz, 3x faster than the previous design. In addition to its 1Mb of error-detecting and correcting (EDAC) memory, it has 16Mb of RAM and 16Mb of Flash memory for mass storage.

The IFC board includes two GMSK modulators that can operate up to 115K Baud, and six

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GMSK demodulators that can operate up to 14.4K baud. Also included is a PL tone decoder.

The Spacecraft Operating System (SCOS), also flight proven on numerous spacecraft.

Hardware and software development are facilitated through the use of the SpaceQuest "FlatSat" model, see Figure 5.

Spacecraft Flight Software

The boot loader provides the minimal set of functions required to verify the satellite health and load the operating system. The bootloader is being tweaked to improve the uplink.

The Spacecraft Operating System (SCOS) has been used on all of the Amateur Radio Microsat projects to date. Harold Price has agreed to allow AMSAT to use SCOS in AO-E without charge.

The Mission Software provides complete control over all aspects of the satellite, including experiments and attitude control. This software can be loaded into FLASH from the ground after launch.

Power Generation and Distribution

The AMSAT OSCAR-E Power Subsystem consists of a Battery Control Regulator (BCR), GaAs solar panels, matched flight cells, voltage regulators and a power activation switch.

The Battery Control Regulator (BCR) converts solar panel power to system power, and manages battery charge and protection. It is a switching design with a measured efficiency of 89 percent.

Six GaAs Solar Panels, which are mounted on all six sides of AMSAT OSCAR-E, produce a bus voltage of approximately 16 volts. The cells that have been purchased for AO-E are among the best available, with
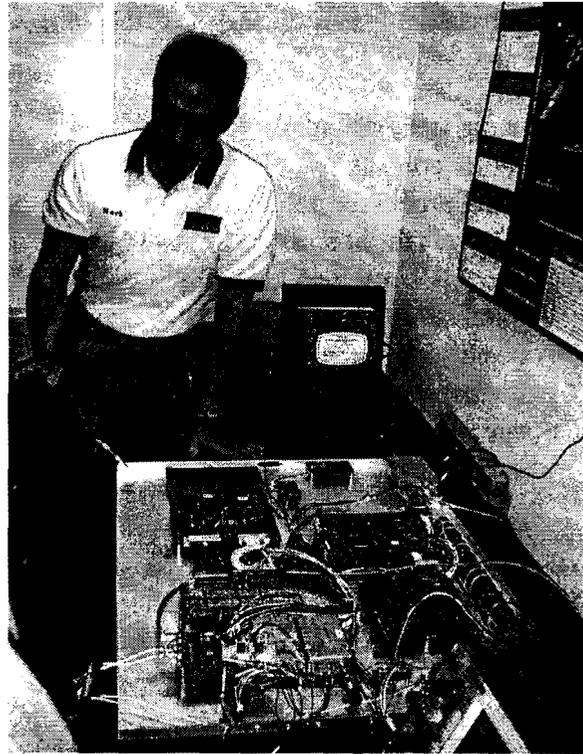
Figure 5 - Mark N4TPY with "FlatSat"

conversion efficiency of over 25%. Mark Kanawati will personally do the layout of the cells onto the panel. He proposes to fly without a glass cover on the cells, which requires more careful handling but gives an additional 1.5% in output.

The battery configuration is a matched set of six NiCd cells at 4.4 Ah each with a nominal battery voltage of 8 V dc.

The BCR provides multiple switched 8-V lines for both transmitters and other high power applications. There are also 3.3-V and 4.6-V switching regulators, capable of over 250 mA output each, with multiple switched and unswitched outputs.

Command and Control – Ground Station

The Bootloader application communicates with the satellite's bootloader upload code changes or to load and execute operating system tasks.

The Housekeeping program communicates with each of the tasks onboard the satellite.

The Telemetry Gathering and Reporting program downloads and displays satellite health information.

Each of these programs need to be written or re-written by AMSAT volunteers! This task has not yet been assigned.

Receivers and Transmitters

Four miniature VHF FM SpaceQuest receivers are used for both command & control and for user links. Each receiver consumes less than 40 mW and weighs less than 50 gm.

Two SpaceQuest UHF FM transmitters provide the downlinks and can be operated simultaneously. Nominal power output is 7 watts. The transmitter modules are being redesigned to reduce their overall height and to move the connectors to one end.

Antennas

The VHF antenna consists of a very thin quarter-wave (18-inch) vertical whip mounted in the center of the top surface of the spacecraft.

AO-E has a UHF Turnstile Antenna that is fed by a strip line hybrid antenna phasing network that provides the appropriate quadrature phase and amplitude to each of four output antenna ports to produce true circular polarization over a wide range of squint angles. As currently designed, the turnstile provides left hand circular polarization. SpceQuest is looking into redesigning the turnstile for right hand circular polarization but this may not be feasible.

Three additional antennas are provided in a cluster in the center of the bottom face of the satellite. One is an 18" whip with dual feed electronics to feed the LF/HF/VHF/UHF wideband receiver. This antenna is still under development. The other two are ¼

wave whips for L and S bands to support a proposed Mode L/s transponder.

Link Budget Data

The following data is approximate and is provided for those wishing to make preliminary link budget calculations.

Transmitter: 70cm band, fixed frequency crystal controlled. Power output is 12 Watts maximum and is adjustable over a range of 1 to 12 Watts. The best efficiency achieved at 7 Watts output. There are two transmitters that can be operated simultaneously.

Hybrid Coupler: The two transmitters are combined to feed one antenna. Loss in the hybrid coupler is about 0.5 db or less.

UHF Antenna: 1 to 2 dBic gain (2dBic at ±40 degree squint). See Figure 6.
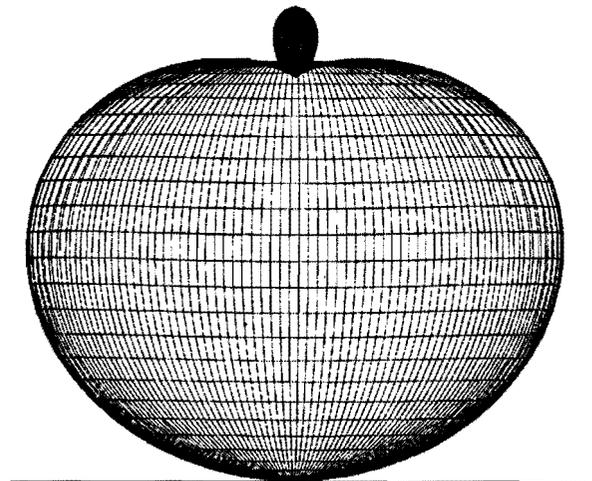
Figure 6 - Turnstyle Antenna Radiation Pattern

Note that with these numbers it is possible to exceed the FCC recommended power density of -125dBw/m^2 per 4kHz bandwidth.

When transmitting data the waveform is GMSK ("softened" FSK, not phase coherent like true GMSK). The data rate can be set to anything up to about 56K baud, limited primarily by the FCC channel bandwidth limit (100KHz).

Normal operation will probably be at 9600 baud to be compatible with all the radios and modem that are commonly available.

Receive Antenna: A 1/4 wave whip in the center on the face that normally looks up when over the Northern Hemisphere. It has about 1.5dBi (linear) gain.

Receive Cable and Filter assembly: 1dB loss.

LNA: 0.7dB Noise Figure. 18dB gain.

Receiver: 15KHz Bandwidth in voice or data (supports up to 9600 baud data).

OPTIONAL PAYLOADS

The optional payloads under consideration for the AMSAT OSCAR-E mission have been described previously so only status information is provided here.

Advanced Data Communications for the Amateur Radio Service (ADCARS)

A number of meetings and discussions have been held with KA9Q, W2GPS, SpaceQuest and others. This is a difficult and poorly understood project. Much more work will need to be done if AO-E is to provide meaningful support for the development of this new technology.

L-Band/S-Band Communications System

This project may be combined with ADCARS. A project leader with experience in wide band transmitter and receiver design is needed.

GPS Receiver

AMSAT, headed by W3IWI, is still looking for a suitable candidate for this. Power consumption, size and weight of available equipment are the limiting factors here.

Active Magnetic Attitude Control

This project has been embraced by SpaceQuest and is now a part of the core spacecraft design.

Audio Recorder Experiment

This experiment, proposed by KK7P, will provide the capability for recording and playing back any audio channel. The CPU is also needed to support ADCARS. There is no progress to report on this project at this time.

Low Frequency Receiver

To become feasible, a way must be found to share the single 18" wideband receive whip between low frequencies, using a new E-field antenna interface amplifier, and VHF/UHF frequencies, which use a more conventional interface.

APRS

APRS can be supported in various ways through software only solutions. While it would be best to develop the software while the satellite is still on the ground, it is not essential. A volunteer is needed to do the software development.

PSK-31

PSK-31 will be supported by operational control. No additional development is necessary.

Multi-band Receiver/Antenna

This receiver is now a part of the core satellite system. The capability is limited only by the antenna design, which must be finalized.

High Efficiency Solar Arrays

This is now a part of the core satellite system. Cells have been obtained that have conversion efficiency in excess of 25% and will produce over 7 Watts per panel when facing the sun.

Robust Telemetry Link

Discussions continue with KA9Q regarding implementation issues. This is another very valuable project that is now well understood.

CONCLUSION

The core elements of AMSAT OSCAR-E are under construction now by SpaceQuest.

The AMSAT OSCAR-E project team is still working to finalize plans for optional payloads. This is proving to be especially difficult.

It is hoped that AMSAT OSCAR-E will be the first in a series of new low-cost LEO satellites, each to carry optional payloads of interest to the AMSAT community.

Microsat Design
What Do People Want?
Richard M. Hambly (W2GPS)

As AMSAT-NA returns to the business of satellite construction it appears that the world around us has changed significantly. But in some very important ways our world has not changed much at all. The following are my observations and suggestions.

PROBLEMS I SEE

After months of searching for qualified and motivated leaders and developers for AO-E's optional payloads without much success, I observed these same types of people joining up with AMSAT-DL's Mars program and flocking to build CubeSats.

BACKGROUND

In January 2001 KA9Q presented a radical new proposal for a wideband digital communications pipe that would finally allow for practical use of the bands above 1GHz on LEO satellites, without the need for high performance Doppler tracking. The AMSAT-NA Board endorsed the concept and offered further encouragement.

In July 2001 AMSAT-NA hosted a meeting of the new Project Committee in Denver CO. The goal was to decide on the design parameters for "Eagle" and discuss emerging technologies. The result was a conservative design with spin stabilization, Mode U-L/S linear transponder, Mode L/S wideband digital transponder, and a GTO orbit requiring no (or very little) propulsion.

In January 2002 AMSAT-NA also approved building a Microsat class LEO satellite. This satellite could be launched much sooner that "Eagle" and would provide a successor to AO-27. In order to get a reliable design built on a rapid schedule, AMSAT-NA approved having the satellite built by our friends at SpaceQuest. This also provided a tray for our builders to add whatever new feature

they desired and a variety of proposals were evaluated.

In April 2002 the AMSAT-NA Board voted to
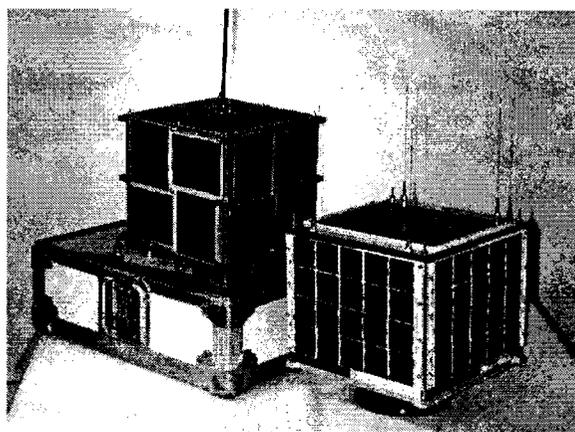
Figure 1 - Microsat and AO-E

extend the AO-E launch schedule to late 2003. This was done, in part, to give the builders more time to get an optional payload on the satellite.

THE USER COMMUNITY

As soon as the schedules were announced, users began expressing their opinions about the features they want to see in the new satellites. These users tend to fall into a few broad groups with different perceived needs.

EasySat Users

EasySat users are generally categorized by those with simple antennas and one or two HandieTalkies operating FM voice on the 2-meter and 70-cm bands.

Figure 2 - EasySat User

For the most part these users seem quite pleased by AO-E's core design, which can support two simultaneous high power Mode V/U FM voice channels.

Linear Transponder Users

Linear transponder users are generally characterized by base stations with computer tracking, 2-meter and 70-cm beams on a Yaesu Az-El rotor with computer steering. Many of these stations have added Mode-S receive antennas and some have added Mode-L transmit antennas to their antenna arrays.

Some of these users have expressed disappointment in AO-E because the core package offers nothing of interest to them and none of the optional payloads offer a traditional Mode-B or Mode-J linear transponder.

These users who are waiting for "Eagle" and many of them see AO-E as an irritant that will only serve to delay the launch of "Eagle".

APRS Users

APRS users are generally characterized by 2-meter mobile and portable operation using 1200 or 9600 baud AFSK. A few of these stations are dedicated base stations with sophisticated software to monitor the various LEO satellites as they pass over and route any APRS packets they hear to the Internet (IGATE stations).

These users see nothing interesting in the "Eagle" project. They are generally dissatisfied with AO-E because they want to reverse transmit and receive bands (Mode-B instead of Mode-J). This would improve the link budget for these stations that usually have plenty of power but have marginal receive capability. It would also eliminate desensitization of their 70-cm receivers by the harmonics of their 2-meter transmitters.

Users with Limited Capabilities

These are users that generally cannot set up home stations because of restrictive covenants, living in rental property, apartments and condominium dwellers, etc. Some of these users belong to AMSAT simply to be able to receive the Journal and support AMSAT. Many of these users compensate by becoming part of the builders group or by operating in one of the mobile/portable categories.

Many of these users would benefit from implementation of the wideband Mode L/S communications system proposed by KA9Q but, surprisingly, there has not been a groundswell of support from this group yet. Many simply don't understand the concept.

BUILDERS

AMSAT's builders group includes individuals that design, construct, test, launch, control and experiment with the satellites. AMSAT's builders have traditionally been an independent

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group of scientists, engineers, technicians and others who build what they want, each using their own personal style. Builders, as defined here, don't actually have to build anything. Some are idea people, others do conceptual design and others do post-launch analysis.

Many of these people do not even have a satellite station at home but when they do the stations tend to be very sophisticated.

The builders tend to work behind the scenes. Most don't check into nets, operate DX on the satellites or send messages on AMSAT-BB. They are most visible at events such as Board meetings and at the AMSAT Annual Meeting and Space Symposium.

Most of the builders view their involvement as "professional" even though they are volunteers. Some of the most prolific have used their amateur satellite involvement as a springboard for real professional activities.
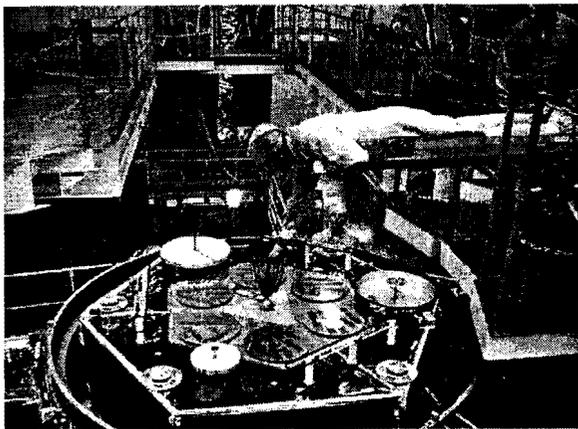

Figure 3 - Motivation

So what do the builders want? The two things that seem to be of greatest importance are technical challenge and/or recognition. For example, when AMSAT-DL proposed a mission to Mars AMSAT-NA builders started lining up to get on the team. It matters not that none of the people in the users groups will ever hear the signals from

this spacecraft. It is a huge and worthy challenge, and that's enough!

I have not observed that same level of enthusiasm for AO-E and "Eagle". Why? Perhaps it is because these satellites pose few interesting new challenges.

Another characteristic common to many of our builders is that they are an aging group. They are a decade older than when they built the original Microsats. Certain of their skills show signs of age, too, especially in areas such as software and wideband communications techniques. There are very few new young builders in AMSAT but there are young builders out there, as has recently become evident at the 16th Annual AIAA/USU Conference on Small Satellites held in August 2002 at Utah State University. Many of them just haven't been introduced to Ham Radio. Unfortunately many of these people don't fit the mold of classical amateur radio at all. Some may be get a license solely to be able to fly their satellite. Thus, the interest shown by some universities in building and launching satellites can be both a challenge and an opportunity for AMSAT.

I have also learned that some builders place a high value on AMSAT's Area Coordinators and "Elmers" as an interface with the general membership and others, allowing the builders to focus on their tasks.

GENERAL MEMBERSHIP

The one characteristic common to the general membership and other onlookers is their demand for a complete, honest, and timely flow of information. This is especially true if the news is bad.

When there is even a slight delay in the timely flow of information, the result is a perception that "they" are keeping something important from "us". This attitude is infectious and invariably negative.

The advent of the Internet has enabled everyone to become an instant critic. Some feedback is good, some degenerates into tangents, some is downright counterproductive and some even exhibits blatant violations of the laws of physics. Most of the builders ignore the feedback because S/N is so poor.

It has been observed that many of those who complain the loudest are not even AMSAT members.

TECHNICAL CONSTRAINTS AND OTHER CHALLENGES

Every year the advances in technology have enhanced our ability to put more features in less space than ever before. Unfortunately, commercial interests have discovered the same thing and what was once a free ride as ballast replacement is now a muti-million dollar cost driver for our projects.

Software is becoming more important than ever. We can now implement modems using sound cards and DSP software, which is driving TNC manufacturers out of business. But how many of us understand modern techniques of software development or the mathematics needed to grasp DSP and coding theory?

Colleges and universities around the world have recognized these facts and have changed their curriculums to accommodate the changes. For example, Cornell University first started a small Computer Science department as a joint venture between the Engineering and Liberal Arts Colleges. Now the Computer Science department has merged with the Electrical Engineering School to become the School of Electrical and Computer Engineering. But traditional skills essential to developing a satellite like RF, analog and digital design, are getting harder to find.

WHAT'S WRONG?

AMSAT-NA is trying to be responsive to the perceived needs of the average user while being realistic about what it will take to get at least one satellite launched within a reasonable time frame. This is considered essential to rebuild our image and membership roles following the recognized and publicized problems with AO-40.

These goals, while well motivated, overlook two realities that have, in the past, driven the development of our satellites – a real launch opportunity with a fixed schedule and the desire of the builders to build. All AMSAT-NA's past successful missions have grown from a launch capability and opportunity. Because of commercialization, launches for small satellites have become more and more rare and costly, and we compete with DoD, Universities and commercial entities for launch opportunities.

In the case of AO-E we believe we have that launch opportunity but it needs to be firmed up. In the case of "Eagle" we don't know how and when it will get launched.

Providing motivation to the builders is much more difficult. I am hoping that by reconsidering some of our design parameters for both AO-E and "Eagle" we can create the kind of technical challenges that will bring the builders to the design table.

In addition we face challenges to our frequency spectrum from commercial, industrial, defense and other scientific users. We also face challenges on the regulatory front, especially in the area of space debris mitigation, that could drive the cost of launching satellites beyond our reach.

MY RECOMMENDATIONS FOR AO-E

The following changes to the AO-E design are proposed with the goal of creating a LEO

platform that is an ideal transition between the past, present and future technologies. The core platform being built by SpaceQuest is already well suited for this mission and all of these changes can be accommodated by this platform if AMSAT can provide motivated builders to make it happen.

A) Reinstate the gravity gradient boom stabilization. Find a way to ensure that it stabilizes right side up. This will insure that AO-E will always point down with an
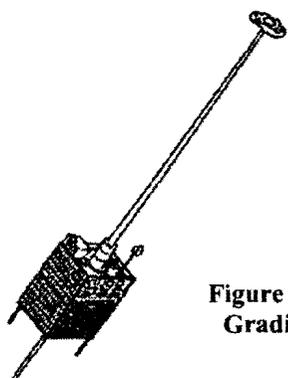

Figure 4 - Gravity Gradient Boom

accuracy of about 5 degrees.

With this improvement the satellite will be equally effective in either hemisphere and will be able to support high gain antennas creating a potentially huge savings in power consumption.

B) Design new FM transmitter and receiver modules so we can switch to UHF uplinks and VHF downlinks.

In this configuration the transmitters could be optimized for 1-2 watts instead of the current 7-12 watts, improving our power profile.

While this frees the users from most cross band interference and desensitization issues, it creates those issues for the satellite designer. Perhaps it's best to solve these issues once on the satellite rather than forcing every user to solve them individually.

C) Add a Mode B Linear transponder sharing antennas with the FM receivers and transmitters.

This capability would give support to the traditional SSB/CW user. This mode will support the most simultaneous users in the near term and will provide some real opportunity for chasing DX.

D) Build the Mode L/S transponder and a high speed modem to support development of the wide band technology as proposed by KA9Q.

Wide band technology is needed to support practical use of the microwave bands on LEOs. There are many challenging issues here that could be the subject of an entire paper. This is truly the future for LEOs.

E) Implement encoding for AO-E's digital downlink channels. The coding should be optimized to compensate for the various types of noise and fading that can occur on a satellite link, for both normal and abnormal conditions. If possible, the coding should also enhance the link margin through coding gain. The solution will likely be some combination of Forward Error-correcting Codes (FEC) and interleaving.

Use AO-E to prove that all telemetry and command downlink channels on all future satellites should be encoded for maximum performance at minimum power.

MY RECOMMENDATIONS FOR "EAGLE"

The most significant challenge for "Eagle" is to achieve a favorable orbit regardless of the launch opportunity. To optimize the usefulness of this high flying satellite this is probably not a GTO orbit.

1) Plan to go to a useful and interesting orbit. I propose that we consider one of three interesting orbits, the standard Molnya orbit, a geosynchronous orbit, or a high Molnya orbit now used by the Sirius system[1].

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The high Molnya orbit would keep "Eagle" above the Van Allen radiation belts. Admittedly, it takes lots of energy to get there, but I didn't say it would be easy.

2) Put a motor on "Eagle" that is sufficient to achieve the goal or reaching the desirable orbit. There are a variety of technology choices, some involving one or two tanks of liquid fuel and others using solid fuel.
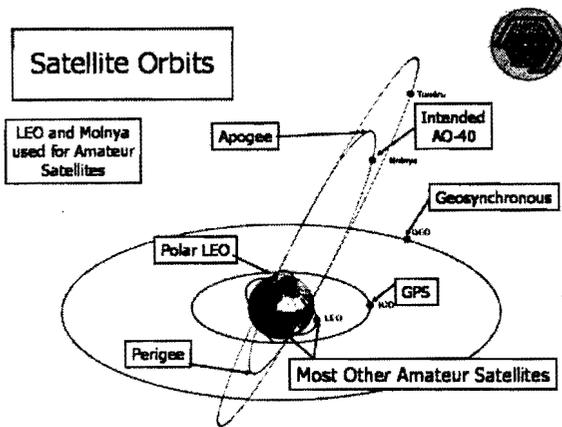

Figure 5 - Orbits

Implementation of these suggestions would probably have a significant impact on the size, weight, and cost of "Eagle" and would raise significant launch issues.

COST

Many of the questions and thoughts in this paper are influenced by a lack of available funding. If AMSAT is to remain as the leading amateur radio satellite entity, then the membership must be prepared to provide sufficient funding to meet their requirements from the organization. We as members of the Amateur Radio community willingly spend a great deal on our equipment. Some of us even spend a dollar or more a day on coffee. But many of us don't or won't spend even 30 cents a day on supporting AMSAT.

If you want AMSAT to produce the goods - then you must support AMSAT. Most of the above suggestions, although very desirable, are expensive and funding to carry them out is necessary - what can you do?

CONCLUSION

If AMSAT-NA is going to build its own satellites again, it must fire up the imaginations of the builders. No amount of user satisfaction or fund raising will substitute for this!

Our builders must be replaced over time! We need to cultivate a crop of new, younger, builders and ask our experienced builders to act as mentors. With the shrinking rolls of Ham Radio, propped up somewhat through the new no-code licenses, we will probably have to look outside Ham Radio for these people. The colleges and universities are our best hope. AMSAT will need to work hard to get talented young people into Ham Radio and into AMSAT.

Finally, AMSAT-NA needs to serve the broad user community through education, information, and activities that promote the feeling of belonging. AMSAT-NA also needs to restore its membership rolls to the levels of a decade ago to help maintain its financial vitality.

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[1] Sirius Press Release: Sept 5, 2000 09:43 GMT. Nation: USA. Launch Site: Baikonur . Launch Complex: LC81L. Launch Vehicle: Proton 8K82K / DM3. Sirius 2 Class: Communications. Spacecraft: FS-1300. Agency: Sirius R. Manufacturer: Space Systems/Loral, Palo Alto. Perigee: 24,521 km. Apogee: 47,051 km. Inclination: 63.4 deg.

Sirius Radio's Sirius 2 was launched into a 144 x 168 km x 64.8 deg parking orbit. The Blok DM3 stage then made two burns to deliver Sirius 2 to an elliptical 6192 x 47057 km x 63.4 deg orbit. The was to provide digital radio broadcasts to mobile users in North America. Stationed at 64 deg W. Last known longitude (31 August 2001) 64.56 deg W drifting at 0.003 deg W per day.

So You Want to Build a Satellite! – Revisited
By: Dick Jansson, WD4FAB

Abstract
Two years ago, at this forum, an Amateur Satellite program was proposed. This proposal outlined a low-cost, "simple" satellite design to fulfill the future needs of the Amateur Satellite Service. Actually two designs were proposed by different authors, and they have since been merged into one program. Those proposals have moved forward into the serious design stage in a program that we now call "Eagle". It has been discovered that not all of the initially proposed, lofty goals can be met, but the work done to date shows a considerable promise for a viable and reproducible spacecraft design. The principal goals of an all-solar-attitude, low-cost, geosynchronous transfer orbit (GTO) design have been retained and have produced a design tailored to fit a number of launch environments. This paper will describe the work done so far, and set forth the work yet to be done.

Here We are Again
Two years ago, at this forum in Portland, Maine, several satellite ideas were placed on the table for your consideration.[1] Since there were some "competing" concepts for our next satellite, a meeting was called in July 2001 in Denver, Colorado, to resolve those concepts into a singular effort. At that time, we did not even have an "official" name for the program, it was called "JJ" (derived from the first letter of the family names of the authors, and a matter on which Lyle Johnson and I were both agreed had to go). This paper presents to you the results of the work done since Denver, showing a satellite design that we now call *Eagle*, a coalescence of the not-so-different ideas that were presented to you in Portland, but a design that is felt to provide a broad tool for our use in the future. This design has the flexibility to provide service for many different applications, not just those of our Amateur uses.

Design Goals
Let us review the basic design goals of the Eagle program. I shall do some recounting of the objectives placed on the table for you in Portland, as most of those survived the review in Denver.

We are still looking at a satellite that will provide us with the benefits of the wide-area coverage that can only be provided by high-altitude operation of the satellite, as we had in the previous Oscar 10 and 13 (AO-10, AO-13) satellites and that we have now in Oscar 40 (AO-40). We are still working to hold to the basic AMSAT design tenets of KISS[2] for this design. Let us look at these key points provided for this program in my prior presentation, and see how our current effort stands up to the proposed goals.

- High altitude orbit for wide area coverage and long-distance DX operations
- Transmitting and receiving equipment for wide-band, multi-user SSB operations
- No propulsion
- No more than three years from start to launch
- Cost less than $500,000
- Re-use as much prior design technology as possible
- Weight less than 50 kg

The orbital goals for Eagle are for a modified GTO[3] where we would need to lift the perigee to between 500-1000km, for a stable orbit and reasonable lifetime. It used to be that an Ariane 5 launcher would provide us with a GTO that met these goals with no propulsion needed on our part. AO-40 was launched into just such an initial orbit. So much for great ideas. The newer, restartable Ariane upper stages now provide the more conventional GTO lifts to space, ending up with ≈200km perigees. So Eagle will need to carry a propulsion system, but we are working hard to select such a system that is as simple and easy to handle as is possible. Lifting the perigee of a GTO satellite does not need a large amount of propulsive energy, 30-60 m/s, so we can still keep it simple, even though we cannot avoid a propulsion system.

One of the problems seen with all of the Phase 3 satellites launched to date is that they all have been designed to operate at high orbital inclinations, and every one has failed to really achieve that desired goal. As a result, the solar power production on the satellite has been inadequate for parts of each year

of operation. To maintain minimum solar power generation, these satellite's antennas have had to be off-pointed from the Earth, pointing them away from the users at optimum operating times. Sadly, we see this with AO-40 these days; there are "seasons" of operation, at least until AO-40 is brought under its stabilized operating mode. One of the basic design features of Eagle is to overcome this very problem by providing full power operation of the system regardless of the sun-angle (Beta angle,β). This very situation is the reason that *two* basic satellite designs were offered to you at this meeting two years ago, each one solving this solar power problem in a different manner. There will be more on this point later in the paper.

The creation time of this design will not meet the initial goal of having a program that is just three years long, as another, short-term AMSAT program has intervened and drained some resources from the Eagle program. That difficulty has not slowed some of us down on the Eagle effort. However, another factor is slowing the Eagle program down, that of having a launch opportunity at hand. A launch would be available for us anytime that we would want to pay full fare for an Ariane 5 ride, but that is a $2,000,000 matter, much more than the construction phase, and more than we have readily available.

This draining of resources is costing the Eagle effort in the electronic area, and I can report that we do not yet have a stable full of electronics ready to be mounted into the spacecraft. One proposal that had been placed on the table in Denver was that of an all digital voice mode of operation. Reality caught up with those proposers's when it was realized that the ground station requirements would exceed any reasonable budget and that the satellite's resources could not support the all digital operation.

We are meeting the goals of reusing as much of prior design technology as possible, as we have a number of the key players from the P3D effort also working on Eagle, and we very well know how to borrow ideas and reuse them.

The weight issue of being less than 50 kg will easily be met with the exception that the propulsion "juice" may cause us to exceed that limit. This one is still on the table at this time. So with all of these caveats, let us dig into what Eagle looks like at this time.

Eagle Spaceframe Design

Eagle's design starts with deciding some basic mission parameters. The first is to decide by what methods that the satellite will be stabilized in orbit, so as to be able to orient the antennas in desired directions. The details of this point are what caused two designs to be offered in Portland. One design, proposed by myself, followed the past practices of orienting gain antennas, and spin axis, in the orbit plane toward the Earth with the satellite at apogee. Away from apogee, the antennas will be operated on their side-lobes, but at lower altitudes. There is a trade-off between antenna gain and altitude that will provide nearly constant signals for Earth stations for a major part of the orbit using this stabilization and orientation method, see a later discussion on this topic. The antenna designs that would be used would employ well known designs. The second satellite design, offered by Lyle Johnson, would maintain the spin axis perpendicular to the orbit plane at all times and employ omni-directional antennas to provide a uniform antenna pattern to Earth stations at all time. The antenna designs for multi-band omni-directional operation had not yet been well defined, and would constitute a major problem to this overall satellite design. The delegates at the Denver meeting agreed that Eagle should go forward with the "spin-axis-in-the-orbit-plane" concept proposed by myself. That decision was quite acceptable by Lyle Johnson, too.

Electronic Modules

Following the Denver meeting, the Eagle design really got started with the electronic module housings. Several of us (the "Orlando Gang", Stan Wood, WA4NFY, Lou McFadin, W5DID, and myself) incorporated our operating experience with the Phase 3D modules and decided to create a design that would be easier to use. It was also decided that the module size of our thought, would be able to fit into most any spaceframe that we were likely to produce. Fig.1 shows the result of this combined experience. This module, the "standard" module design, is called a "200x180", which is the contained PCB size in millimeters. This design is slightly smaller than the medium-size module design (195x200) used for P3D, noting that electronics use less space these days. This design, like those of P3D, are incremented in

units of 75mm, to create larger and smaller modules, thus we have designs for a "125x180" module, and a "275x180" module. Each of the larger modules also comes in versions that also provide for the heat sinking of power transistors.
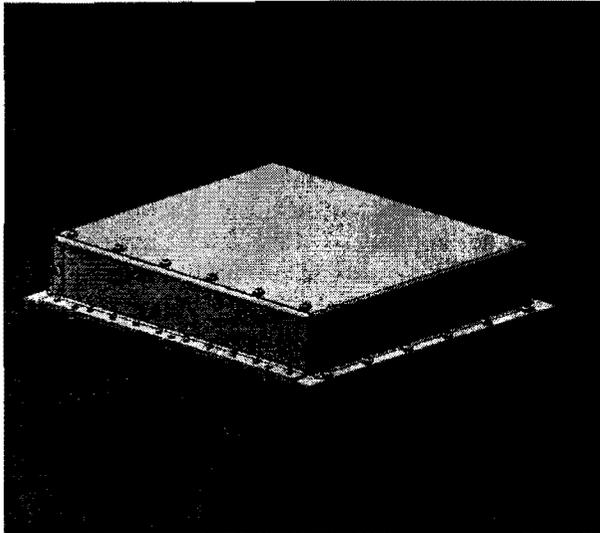

Fig 1 — A computer graphic of a 200x180mm (PCB size) Eagle electronic module housing. Wiring connectors are mounted on the closest side to the left. Save for two screws, the cover is removable while the module is mounted in the spacecraft.

Not yet defined are methods for stacking these electronic modules to provide added capacity and association of modules. Later you will see how these modules fit into a spaceframe. These modules all now exist in manufacturing drawings, ready to build. (We are looking for sheet metal worker-volunteers!)

Spaceframe
The next decision to be made was that of "how big" do we make this satellite design? As we do not have a slot on a launcher yet, we needed to create a design that would be most likely to fit in nearly any situation, be it Ariane, Delta or (?). It was agreed in, Denver, that this design needed to fit into a cube of 600mm on each side, sort of a universal cube. This volumetric constraint then drove the design so that (unfortunately) two sets of solar panels will need to be deployed, once in orbit, so as to achieve the all-attitude solar power generation aspect of the design. Deployable panels (moving parts!) are not in keeping with our KISS precepts, but there seems no alternative in this

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case. If we can launch with the panels deployed, we would like to consider that option.

Fig.2 shows this rather ordinary looking cubical design spacecraft. (After all, what can be exciting about a cube?) With the Y-side solar panels latched down for launch, Eagle just fits inside of a 600mm cube, save for antenna protrusions. On the top, +Z side of the spacecraft, you will see a director-stacked U band patch antenna, a three-patch array for L band, and a four-patch array for S band. There is room for a second S band array. Not yet shown is the antenna for V band, nor any of the omni-directional antennas needed for the initial commanding and for perigee service. There will be more discussions on the RF equipment later in this paper.
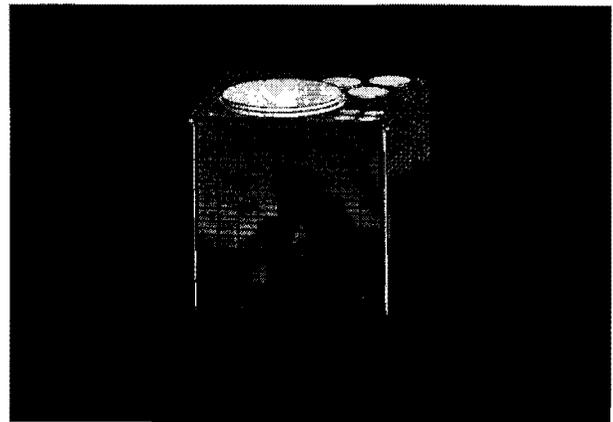
Fig 2 — This computer view of Eagle shows it in its launch configuration with the Y-side solar panels latched down. UHF and microwave high gain antennas are shown on the top, +Z side of the spacecraft.

Fig.3 shows Eagle with its Y-side solar panel wings spread for service. The "V" shaped deployment of these solar panels very amply provides for solar power generation for all solar Beta angles, as will be shown later. The hardware mechanization for this deployment exists! (It is not an arm-waved design.) While it is quite cute to see it work on the computer screen, we will still need to build a full-scale model for testing of this mechanization.
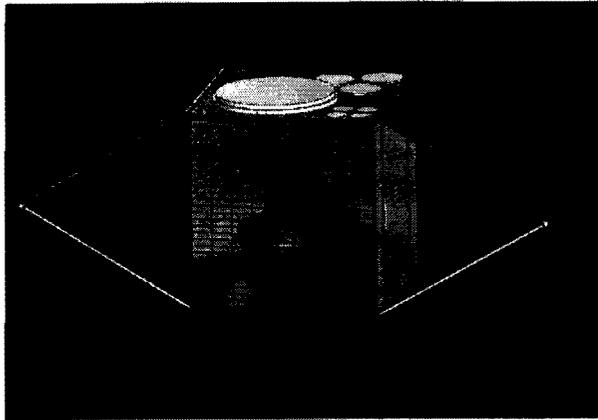
Fig 3 — Another view of Eagle with the Y-side solar panels deployed for full service. Deployment of these panels will be by means of the activation of a cord cutter mounted on the bottom of the spacecraft and torsion springs incorporated in the hinges.

Eagle consists of a core structure of commercial grade, 12.7mm thick, honeycomb panels with 0.5mm thick aluminum-face sheets. We are taking from the AMSAT experience of working with this material class in the P3D program and in the Phase 4 program (which was terminated over twelve years ago). We learned a lot of the practical workability aspects of honeycomb panels in those programs. These honeycomb panels, shown in Fig.4, form a central box with four, 100mm deep compartments around the sides for the electronic modules. The central core "box" is a generous 330x330x598mm compartment to accommodate a propulsion system, which is TBD as of this writing. A simple cylindrical tank of eight gallons can be fitted into this compartment, it is not small! In this de-skinned view of the spaceframe, you are looking down on the +Z top with the +X side closest and the -Y Side to your left. For the lack of any other suitable reference at the moment, I am using these geometric notations to identify spaceframe locations.
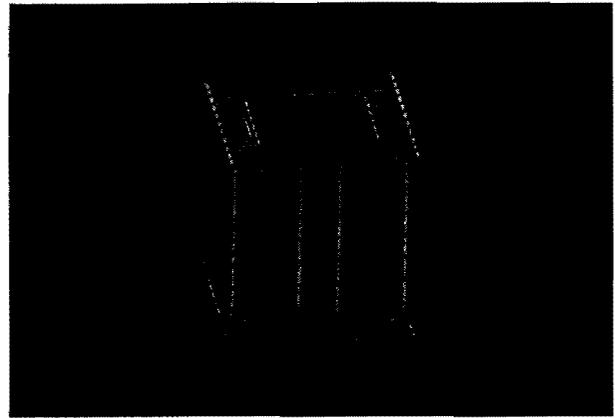
Fig 4 — The core structure of the Eagle spaceframe is illustrated. This simple box structure, made of commercial aluminum honeycomb panels, provides for the mounting of all "weighty" equipment, as an integrated thrust structure, directly coupled to the launcher through the separation mechanism on the bottom of this core structure.

Seen in the equipment bays is an old design element, fiberglass channels for mounting modules to the spacecraft. These are to thermally isolate the majority of the low-power electronic modules, so that their heat is dissipated only by radiation, not conduction. This thermal design feature, first used on P3A (lost in 1980 due to a launcher failure) has since been very successfully proven on other P3 spacecraft, including AO-40. This is also in keeping with the KISS precept of: "if it ain't broke, don't fix it".

How do the modules look in the spaceframe? Fig.5 should give you a very good idea on this question. Shown is the spaceframe with the +X and −Y panels removed. On the +X side, there is an eclectic collection of unnamed modules (two 200x180; one 275x180; and two 125x180), showing a representation of their fit. On the back of the −X panel wall, to the left of the view, in the −Y compartment, you see one of the five-cell, (20Ahr cells) battery assemblies. There will be four of these assemblies in the spacecraft to provide a 28VDC power service, as on AO-40. Also seen are two of the 125x180 modules, the largest that can be fitted into the Y compartments with the batteries. Taking from our P3D experience, a generous wiring and connector trough is placed between columns of modules on the X sides. Wiring holes are also placed near the

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corners of each X panel to provide for the wiring interconnections between compartments.
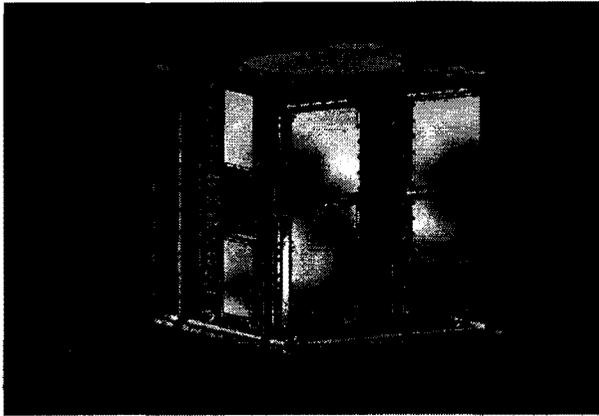
Fig 5 — A representative view of the Eagle spaceframe populated with modules and batteries.

Also shown in this view is the magnetic torquing system, composed of two square rings of computer controlled electromagnetic coils wound on pure iron rods. These rings are located on the inside of the top and bottom panels. The coils will be used, as on all of the preceding P3-mission spacecraft, to control the spacecraft spin rate and pointing angle.

Solar Power

As seen in the preceding illustrations, Eagle has six solar panels. This arrangement satisfies the design goal for generating power at any solar attitude. I have designed these panels for just a single cell lay-down, meaning that the panels all have an identical cell design. As a generic candidate cell for this design, I have chosen a 20x60mm cell. Also for initial purposes, I have chosen the cell efficiency at a conservative value, for these days, of $\eta = 18\%$. Considerably higher efficiencies can be obtained these days, up to an astounding $\eta = 27\%$! These kinds of numbers were not even in our dreams when we designed Microsat some fourteen years ago.

Another feature on the $\pm$X solar panel design is that the panel mounting screw hardware has been minimized to avoid wasting space that is needed for solar cells. For instance, on these body-mounted panels, I have chosen to use 2-56 screws, rather than larger Nr.4 or 6 screws. For this size of panels, I felt that I can get away with this measure, using smaller, but more screws on each panel. As a

result, a little over 90% of the panel area is available for solar cells, often a hard number to achieve in small satellites.

So just what is the expectation for the Eagle power generation? Fig.6 shows the results, from a preliminary thermal analysis, for this cell and panel arrangement. The scale on the right is the solar power generation, and the curve gives power values from a low of about 95W at $\beta = 0°$ up to the maximum power output of up to 135W at $\beta = -70°$. The slight asymmetry shown between $\beta = \pm70°$ is due to slightly different angles of the Y-axis panels on the top and bottom of the spacecraft. Nevertheless, very adequate power will be available for Eagle to use. If you consider that we may well have $\eta = 23\%$ solar cells, rather than the $\eta = 18\%$ cells, then you have to increase the analytic power values up by another 27%, so that the minimum power would be around 120W. All of these values are at the beginning-of-life, BOL, for the solar cells and that we must design for a $1/3^{rd}$ lower power generation for later in the life of Eagle, due to accumulated radiation damage. The numbers still look good, any way that you want to use them.

Thermal Design

The other curve presented in Fig.6 shows an overall expected spacecraft temperature, on the left side scale, for a nominal 50W power dissipation. Nothing special was done for this analysis, and it is not a detailed one, but it is sufficiently close to the desired target as to allow the thermal designer to concentrate on more immediate needs. One of the keys here, fortunately, is that it would appear that we will not need to use the specialized thermal insulation blankets often used on spacecraft, another KISS design goal. The temperatures of Fig.6 show a $\beta = 0°$ temperature of just +1°C with maximum temperatures of +30°C at $\beta = \pm50°$. Fine trimming of this design will probably lower the temperatures by no more than 5°C. For an initial assessment, this analysis does not show any real problems in the thermal area, allowing us to proceed with the remainder of the design. A detailed analytic model of the completed satellite will be produced in due time, allowing the fine tuning of the exterior coatings and setting the final temperature ranges of operation.

I previously mentioned a feature, used in all recent P3-type spacecraft, that of providing conductive

Eagle Thermal Analysis
**Preliminary Design, Model: P3E Mod 2.o03**
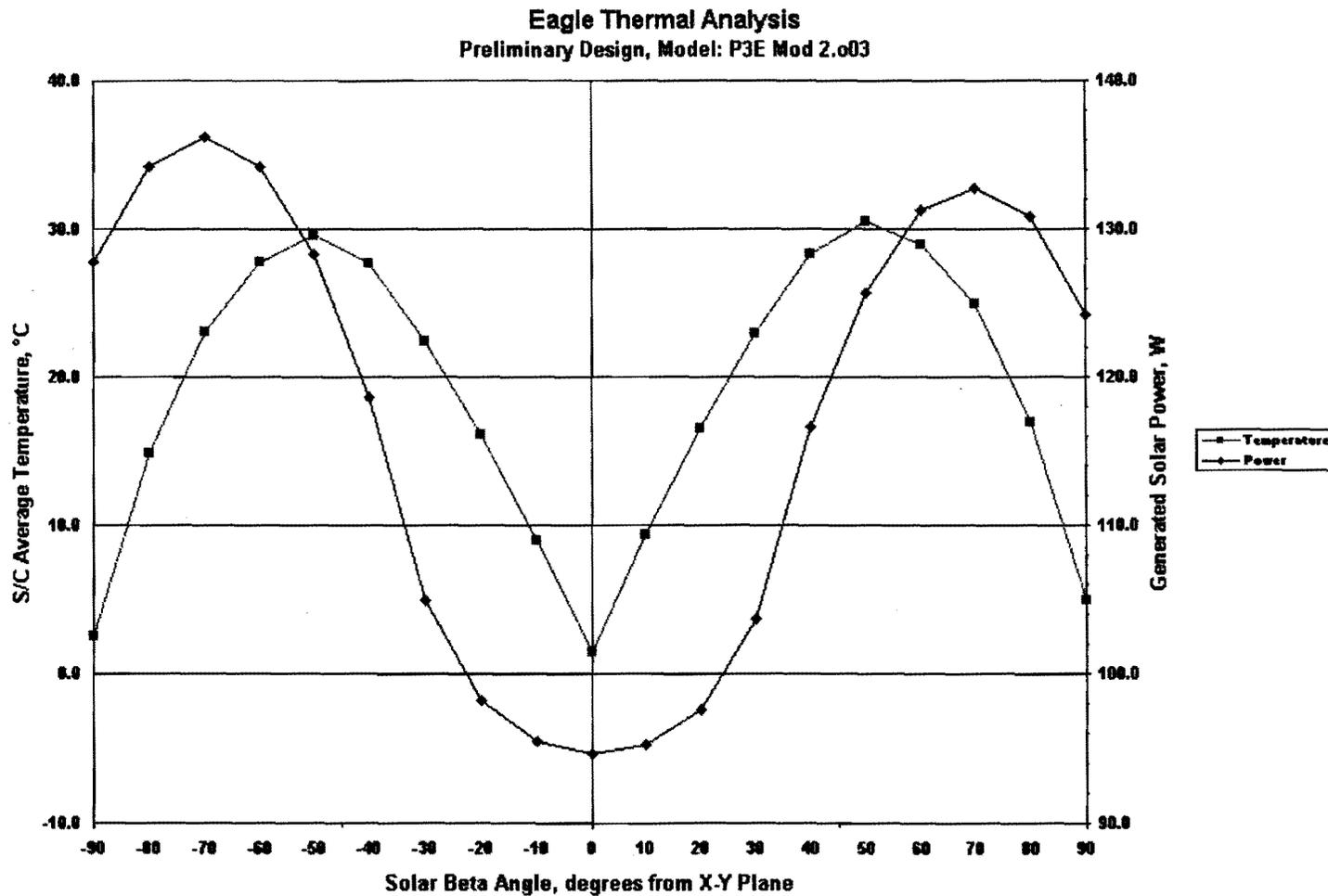
Fig 6 — The results of a preliminary Thermal Analysis of Eagle, showing the all-attitude performance for power generation from the solar panel configuration. The average spacecraft temperatures show that good performance can be expected in this department.

thermal isolation of critical electronic modules from the spaceframe. The reasoning for this, which was very soundly confirmed from AO-10 telemetry, is that when the spacecraft is shadowed from the Sun by the Earth, temperatures drop very precipitously, down less than -100°C, and in a hurry. Such temperatures are not good for the command and control of a spacecraft, stuff might just stop working, which would not be very cool (you should pardon the pun!). Providing a high degree of thermal isolation, especially for these usually low power C&C modules was felt to be worthy, hence the fiberglass mounting channels. This design step allows these critical modules to stay considerably warmer than the very cold spaceframe, maintaining their functionality. The AO-10 telemetry verified this concept, even to having that data overtrace the analysis made many years before that flight. Again, "if it ain't broke, don't fix it".

Thermal isolation concepts will need to be set aside when we consider the handling of concentrated high power dissipations, such as from the power transistors of the RF transmitters. In the P3D program, which has much higher power transmitters than Eagle will see, we used a heat pipe system to redistribute that power. In Eagle we do not have the spacecraft geometry or the device dissipations that would warrant a heat pipe system. Instead, analyses have been done that show that a transmitter could just be mounted on a 6mm thick aluminum plate some 300mm square, for instance, and then let the plate radiate that heat to the spacecraft skins on the inside. This is a simple system that might cost some weight, but it is KISS, and should work just fine. As noted previously, some modules have been designed with an internal heat sink plate that would then attach to this larger plate mounted on the spaceframe. More work will need to be done in this area, now that we understand the principle and the spaceframe geometry.

Launch Design

While as of this writing not much can be said for a launch opportunity, the design preparations for a launch have been proceeding. The spaceframe design incorporates a launch-thrust plate on the bottom (-Z side) that transfers the launch loading into all four core panels making up the central column box of the core structure.

This launch plate incorporates provisions for bolting on an Ariane ASAP5 "Microsatellite" separation attachment. In addition to this mounting, provisions are being made to be able to mount a standard 9-inch Marmon Clamp Band separation mechanism, an old design taken from the Delta program, and often used on the UoSat satellites.

If these launch provisions are not enough, we are also designing an AMSAT separation somewhat based on the design used for our Microsat program, in 1990, and one that is traceable back to earlier OSCARS and a Jan King 1972 design. (Talk about antiquity!) This design uses four precision conical locator pins, on the bottom of the spaceframe. These have respective conical sockets on the launcher side of things. Rather than cutting a bolt, as on a Microsat separation, or opening up a nut, as used on the P3D separation, this design uses a thick Kevlar® cord passing through a tube in the bottom of the spacecraft, and then through a cord-cutter and tensioning mechanism on each side of the mount. The tensioning is just done with a bolt tightening device. The cord cutters are those used routinely on sport parachute operations (and their reliability has been proven!). We plan to provide a redundant design, even though the cutters have great reliability.

So regardless of the launch opportunity, we hope to have the Eagle design prepared for what ever designs may be imposed on us by a launch authority.

Equipment

To this point, I have only been discussing subjects of my training, in the mechanical and thermal areas. The equipment that we plan to be carried on an Amateur-mission of Eagle is depicted in a block diagram chart that came out of the Denver meeting, Fig.7. Please also remember that this satellite is unlike AO-40, it cannot carry every thing (kitchen sinks?) that the whole Amateur population would desire, just the important communications equipment. We determined that uplinks would be in the U and L bands, with redundant downlinks principally using S band, but also incorporating a V band downlink for the lower altitudes of operation, where the demands on antenna gain are not so great. For a spacecraft of the (smaller) size of Eagle, there is just not any opportunity to mount V band antennas with the

Eagle Spacecraft
Block Diagram

L Rx	Digital	S Tx

| U Rx | Switch-LEILA | S Tx |

| Sensors | IHU | V Tx Beacon |

| Cameras | | Magne-Torquer |

| Solar Panels | BCR | |

| | Battery | Propulsion |

Power Distribution
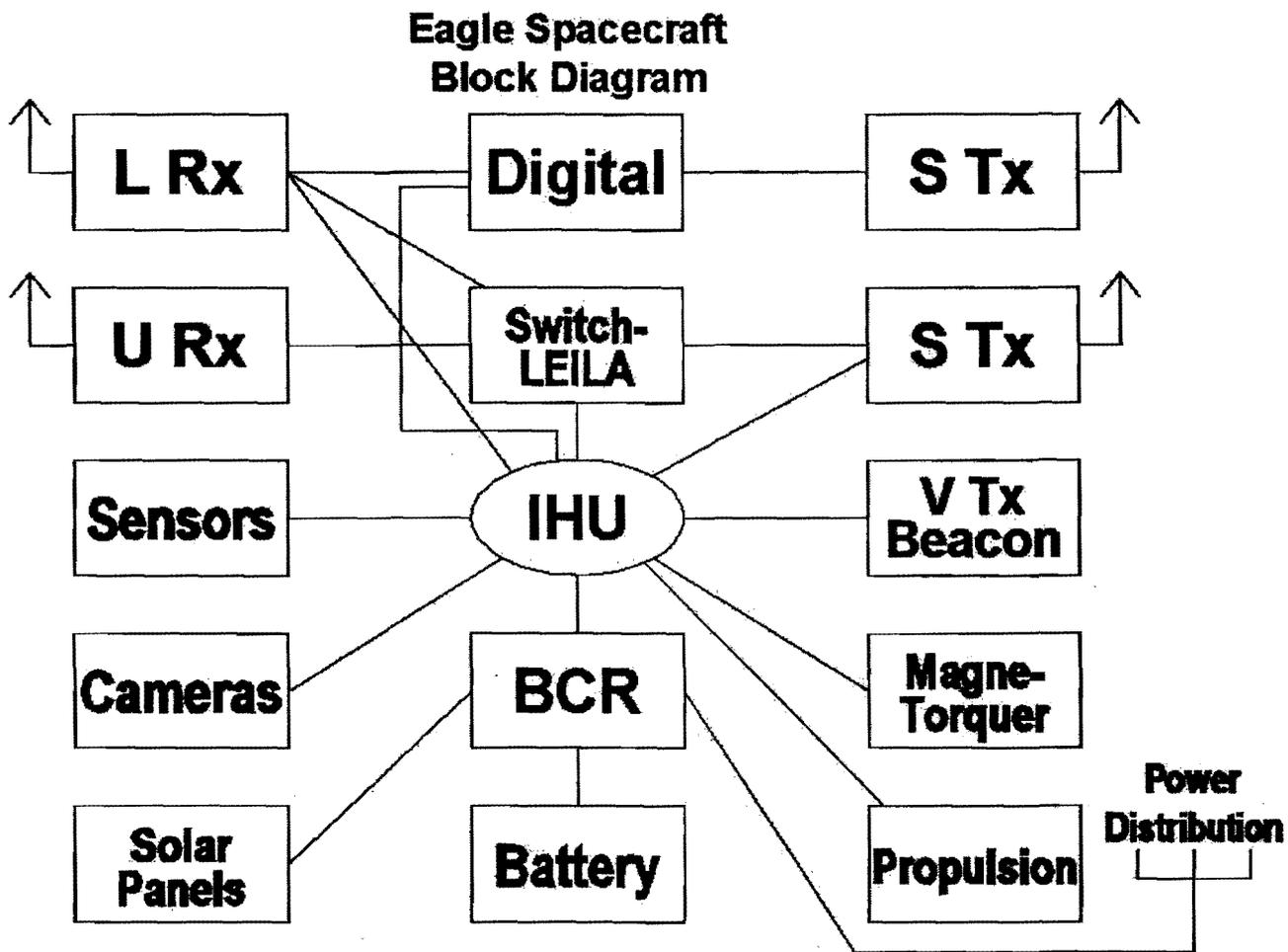
Fig 7 — This equipment block diagram for Eagle was generated at the design team meeting in Denver in July 2001.

Eagle Antenna Squint Angle Analysis
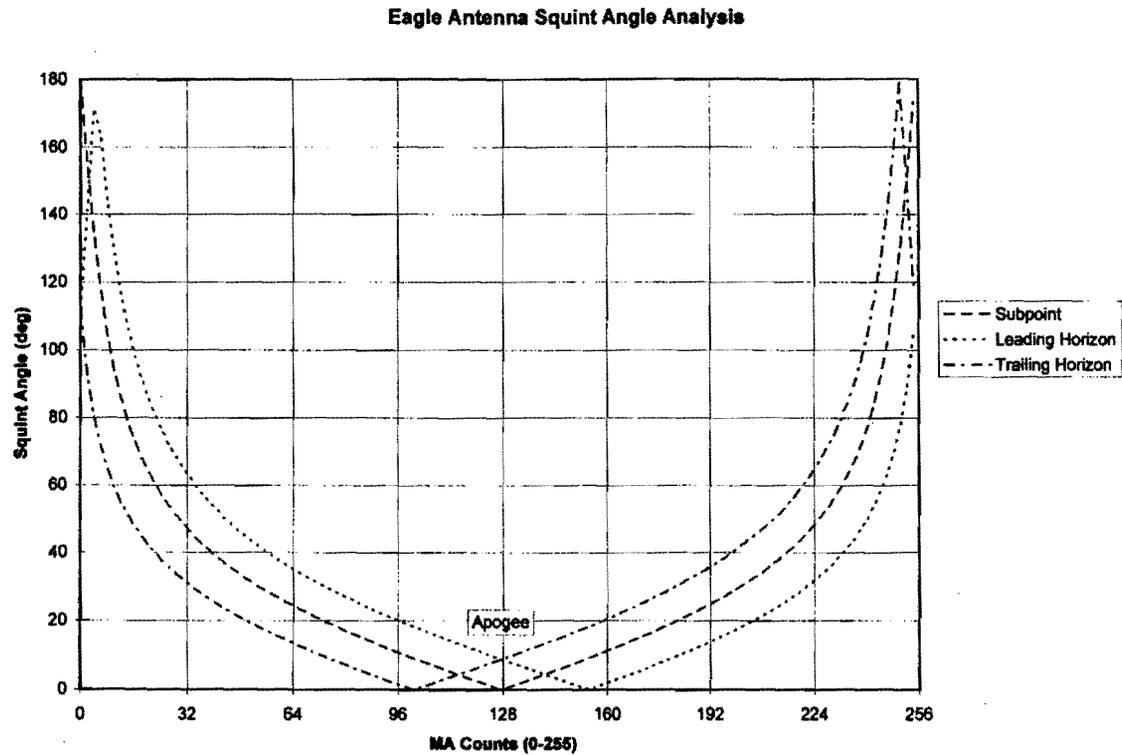
Fig 8 — Analytic results from a study of Eagle's expected antenna Squint angles as a function of orbital position, shown in terms of orbital MA count. This study will guide the determination of antenna gains, targeting for quality communication performances for squint angles up to, and even greater than 30°.

Free Space Path Loss
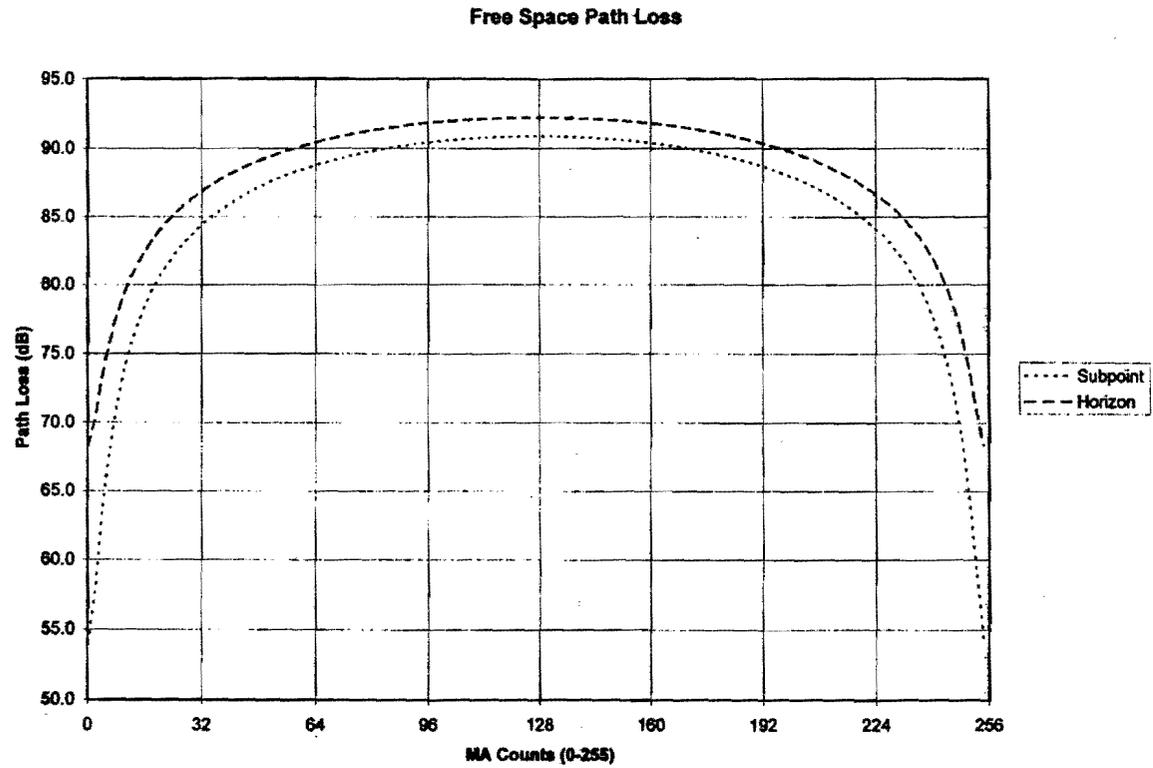
Fig 9—The second chart to be used in the Squint Angle Analysis, showing the Free Space Path Loss as a function of MA count. This chart shows that the reduction in Path Loss is about 3dB at MA = Perigee ±50. The corresponding Squint Angle is about 32°.

kind of gain (≈10-12dBic) needed for operations at the higher altitudes. We wrestled mightily with this point, concluding that V band operations could be included for the lower altitudes, for some ≈40% of the orbit about the perigee, ±50 MA count.

These transmitter and receiver considerations have taken the AO-40 operating experience into account, and found it to our liking for Eagle. Other equipment factors that we considered and incorporated included such things as the cameras, not for the "pretty picture from space" devotees, but at the urging of our command station participants. These command stations have noted the very solid utility of these cameras for the navigation tasks, such as the confirmation of the pointing angles, the ALON and ALAT, of the satellite. Also included are items of necessity, the IHU and BCR modules, and the navigation Sun and Earth sensors. The AO-40 experience in holding down "alligator" stations by the use of LEILA has been beneficial, and so we plan to include that type of unit, too.

The digital aspects of Eagle operation are yet to be determined. The diagram of Fig.7 still reflects the inclusion of a totally separate L-S digital voice operation, but that function will not be in Eagle, as originally thought. The digital function might be another, but much lower power dissipation, RUDAK, as in AO-40. The AO-40 RUDAK is a power hog and its design would need to be "adjusted" to be able to fly on Eagle.

Antennas

Unfortunately, not too much has been done on the antennas, save for what you see mocked-up in my earlier illustrations. These are, however, real and practical patch antennas that we have had some experience in constructing. The real issue is the trade off between antenna gain, altitude, and off-pointing or "squint". With the Eagle antennas pointing toward the Earth at apogee, where the ALON = 0° and ALAT = 0°, there will be an increasing squint angle for a ground station as Eagle is on either side of apogee.

Ken Ernandes, N2WWD, has provided some of the answers to this situation. He has provided the chart, Fig.8, a Squint Plot showing squint angle as a function of Eagle MA counts[4], where MA = 127 is apogee. There are three curves plotted, one for the sub-satellite point, and the other two being the

leading and trailing horizons. Taking only the nominal sub-satellite point for the moment, you can see that a squint angle of 30° is shown for MA of ≈50 counts before and after perigee. Thus a range of squint angles less than 30° is obtained for about 64% of the middle part of the orbit. I will then note that the path loss, Fig.9, for these same MA counts is more than 3dB less than the maximum path loss. This means that if the antenna -3dB half-power beamwidth (HPBW) is about 60° (±30°, the squint angle), then the signal strength will be essentially constant over this operating range, despite the increasing squint angle. And finally, how do we insure that the HPBW is no more than 60°? That is a function of the antenna gain, and typically, an antenna of 10-12dBic will have a HPBW ≈ 60°. Please note also that antennas of this modest gain do not "drop dead" at the HPBW point, they roll-off pretty gently, so that this analysis could go further and extend the practical operating range closer to perigee. But the point is made and this is our guidance for the Eagle antenna design.

Plans

We have a technical team meeting planned for Eagle in Orlando, FL, for late September, 2002, before the congregating of this Symposium. The product of that meeting cannot be reported in this paper, as it is being composed before hand, but will probably be discussed here in Ft. Worth.

Wrap-up

The mechanical design work done so far has been an interesting education, as we have diverged from our nearly constant fourteen year use of Autodesk's AutoCAD design products to go full-fledged into a 3D design environment, using Autodesk's Inventor product. I have found that while Inventor is quite demanding of the computer resources used (and that is another other story on its own!), it is a vastly superior way to create a design. Its productivity has been far better than AutoCAD ever was and it is very precise. The graphics shown are directly from Inventor screen images. An all-up assembly of Eagle with modules and all of the solar cells shown, constitutes a parts count estimated to be in excess of 5000, including every nut, bolt and rivet.

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[1] Proceedings of the AMSAT-NA 18th Space Symposium, 27-29 October 2000.

[2] Keep It Simple Stupid, a rather crass, but basic guidance tenant used to keep the minds of designers on engineering fundamentals, rather than allow them to be drawn to exotic, but not necessarily proven concepts.

[3] Geo-synchronous Transfer Orbit, the intermediate orbit used for the ultimate placement of synchronous, 24 hour satellites. Typically these orbits have an apogee of 35,786km, perigee of 200-300km.

[4] MA or mean anomaly, a fractional unit of time in which the orbital period is divided (in this case) into 256 parts, thus $0 \leq MA \leq 255$ defines an orbital period.

RUDAK DSP – Software Defined Radio in Space

Authors: Assi Friedman 4X1KX/KK7KK, Jim White WD0E, Michael Kingery KE4AZN, Lyle Johnson KK7P, Harold Price NK6K, Chuck Green N0ADI

Introduction

The AMSAT P3D satellite (AO-40) carries a number of experiments. One of those experiments is RUDAK. RUDAK is a German Acronym: Regenerativer Umsetzer fur Digitale Amateurfunk-Kommunikation, which means in English: Regenerating Transponder for Digital Amateur Radio Communications.

RUDAK on P3D is the most ambitious digital communications payload ever built for an amateur radio spacecraft. It includes two identical modules, each supporting seven modems, hardware and DSP based. In addition to the modems both RUDAKS can communicate with two GPS receivers, both SCOPE cameras, CEDEX (a radiation monitor), Monitor (an HF spectrum analyzer) and multiple "smartnode" temperature monitors via the spacecraft's CAN bus. The design of the RUDAK system and its integration into AO-40 has been well documented in numerous papers, publications, and AMSAT's web page.

This goal of this paper is to present the most discussed feature of RUDAK – its DSP modems. The paper will describe goals, architecture (top down), current hardware and software design efforts, and testing by the RUDAK team.

Why DSPs?

The first question that comes to mind is why use DSPs? There are many answers to this, all true and valid in this world of ours we call ham-radio. As hams, our creed is to advance the art of communications. Although the concept of discrete signal processing has been around since the early 50s, technology has made it possible for implementation on a cheap processor only in the mid 80s. Amateur digital radio communications rates over satellites have slowly advanced from a few bits per second by CW, to packet at 1200 bps AFSK, 1200 bps BPSK, 9600 bps FSK and some at 38,400 bps FSK. Up to this point we have had spacecraft which had one or more of the modems implemented. Those modems had a minimum level of agility when it comes to operation. Due to the conservative nature of satellite builders, new modulation techniques were not often introduced into new spacecraft in the past. This is mainly because of the risk associated with the new modes, the complexity of multiplexing several modems into one system, and consideration of the existing user base on the ground.

With the advent of DSP, we saw an entire revolution of system design for the commercial market. DSP took the issues of hardware modem design, threw them out, and turned them into a software challenge. At this point, one hardware design can satisfy many types of modulation schemes or functions altogether.

For the amateur radio community this means the exact same thing. A flying DSP system is now not only a modem, but an experimental platform for new state of the art communications techniques. Until recently, when satellite designers wanted to implement a new feature, they had to wait for the next spacecraft project to come along. With DSP, we are only a pass away from trying out a new modem or application.

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But really, what good would a DSP do on AO-40?

First of all, like all Amateur satellite payloads, the DSPs are an experiment. To the best of our knowledge, they are the first dedicated DSPs to fly on board an Amateur Radio Spacecraft. DSP techniques were used on AO-21, based on a Harris RTX2000-series microprocessor, although AO-21 did not have specialized DSP hardware. The goal here is to learn, and hopefully be a diving board for additional DSPs in exciting new projects.

Now that we have built them and they are in orbit we need to see what we can do with them. At present we know that RUDAK is more difficult to work with than expected. The link budget compounded with the mixing effects in the pass-band reduce the overall efficiency of the downlink.

A DSP is the perfect platform to experiment with modulation techniques that will help improve the link. Additionally, we also have the opportunity to try techniques, which have never been widely tried in amateur radio. These include advanced communications techniques such as Spread Spectrum, Forward Error Correction, and higher order n-array modulations.

Aside from the fact that a DSP is a modem, we should also keep in mind that it is also still a processor. As a processor we can take advantage of its unique processing capability and use it for more than just a communications modem. From this perspective, only the sky and the hardware limitations are the limits. The rest is up to us. There is no doubt that the DSPs on AO-40 can open up new opportunities, it is up to us to embrace them.

Enough talk, what do you want to do with them?

As in every new system, there are several stages to the DSP evolution on RUDAK. The process started with system checkout. The DSPs (as with the rest of RUDAK) are not Rad-Hard, although pre-flight qualification testing indicated they should withstand an integrated radiation dose of more than 100 kRads/Si, or more than 10 years in the expected AO-40 radiation environment. At this point, AO-40 has been in orbit for over a year, and in its current orbit, it passes through the Van-Ellen belts twice an orbit (every 19 hours) Being based on standard commercial parts the system needs to be thoroughly tested before it can be used operationally. This includes both short term testing, and long-term reliability and performance testing. As we do that, we want to also gain confidence in the usage of the system. RUDAK operators did not get much time to try the system on the ground, so a lot of confidence building has to occur on orbit. While this is not too uncommon for AMSAT, this is an entirely new system being broken in.

Once confidence is established, the first goal is to start with the basics. We would like to implement the standard modulation techniques which most satellite operations can already support. This will include 1200 AFSK, 1200 BPSK, and 9600 FSK.

Once the common modulation methods are implemented, new modulation techniques can be tried. Again, there are numerous modern techniques, which are just

waiting for us to dive into wholeheartedly. Some of those might include PSK31 which, although slow, includes modern FEC and modulation schemes. Based on this, newer and faster modems can be designed and implemented. In addition to the modem applications, additional non-modem applications can be written. Some ideas include a spectrum analyzer, a synthesizer to help characterize the IF pass-band, a different test signal for users, and who knows what else?

In general, we could summarize by saying that the approach is to start slowly, with time proven implementations, but future usage is open for development!

RUDAK DSP Architecture

The RUDAK module includes two identical systems. For the simplicity of this discussion, only one will be described. Figure 1 shows the top level design of the RUDAK communications system.
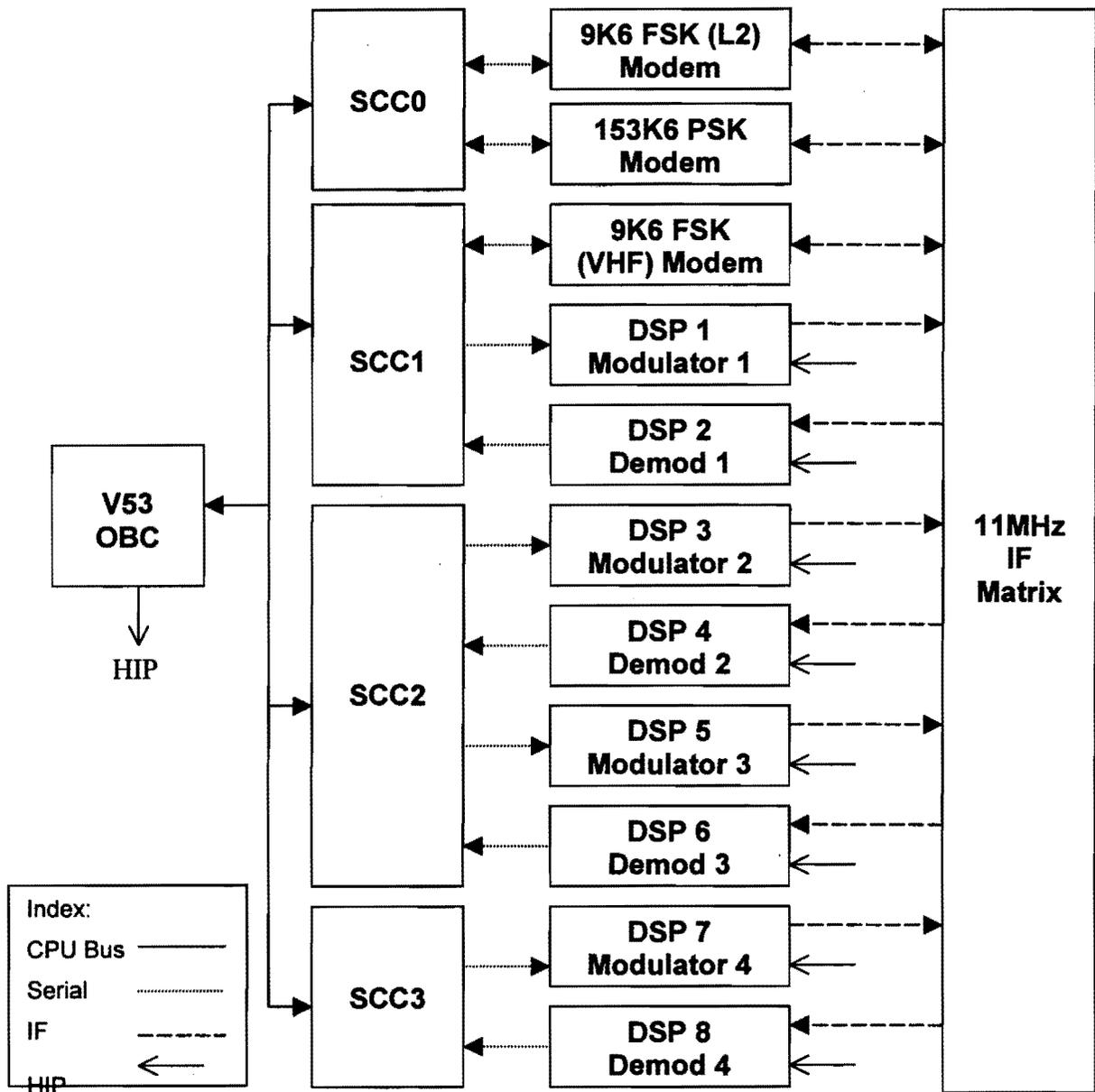
Figure 1 - RUDAK DSP Block Diagram

At the heart of each RUDAK is an NEC V53 based On Board Computer (OBC). This computer runs the Bektek Spacecraft Operating System (SCOS). The OBC has a total of four Serial Communications Controllers (SCC) assigned for wireless communications. Each SCC has two full duplex channels. Therefore, the four SCCs can support up to 8 full duplex communication channels. In reality only 7 channels are utilized for wireless communications. RUDAK has a total of three hardware modems. Two are 9.6 kilo bits per second (kbps) Frequency Shift Key (FSK) modems, and are

compatible with K9NG/G3RUH modems. These modems occupy SCC 0 channel A, and SCC 1 channel B. These are the primary command and control channels. The third hardware modem is an experimental 153.6 kbps Phase Shift Key (PSK) modem. The 153.6 kbps modem occupies SCC 0 channel B. This leaves us with four open channels: SCC 1B, 2A, 2B, and 3A. Each one of those channels is split into two DSPs: a modulator DSP, and a demodulator DSP.

All of the modems, hardware and DSP, interface to the P3D IF matrix. Therefore, these modems all produce an output and expect an input in the 10.574MHz – 11.300MHz range. Using this configuration means that RUDAK can utilize its DSPs in any matrix configuration, and operate in any band AO-40 is capable of.

The DSP modems are based on the same unit, the Analog Devices ADSP2171. By now, this part is already a heritage device, but the ADSP21XX is alive, in production and well supported by Analog Devices. The ADSP2171 contains several key features: arithmetic logic unit, multiply & accumulate, shifter, data address generator, program sequencer, data memory (2k 16-bit words), program memory (2k 24-bit words), timer, two serial ports, and a host interface port. The ADSPs do not have external program or code memory, and are booted directly from the Host Interface Port (HIP) from the OBC. This provides great agility for the RUDAK operator since new code can be uploaded on the fly at any time. The Host Interface Port also allows the OBC and ADSP to establish a basic communications medium via five IO mapped registers. All the ADSPs are fed from a 12.288MHz clock source, but the instruction cycle is twice the clock rate. This provides an effective clock rate of 24.576MHz and an instruction cycle time of 40nsec. The clock rate combined with the parallel instruction execution capability can yield extremely fast processing.

Every DSP is a dedicated one-way channel, i.e. a MO (modulator), or a DEM (demodulator). Since four full duplex channels are supported, this means that each RUDAK has a total of four DSPs working as modulators, and four DSPs working as demodulator. This brings us to a grand total of 16 DSP processors operating on board RUDAK.

Modulator DSP Design

The DSP modulator channels are based on two main ICs: the ADSP-2171, and the AD7008 Direct Digital Synthesizer (DDS). A functional diagram of a single DSP modulator is shown in Figure 2. The DSP receives serial data from the SCC, which in turn is fed by the OBC's CPU. The ADSP uses its serial port (SPORT1) to receive the data to be transmitted (TXD). It is the ADSPs responsibility to provide the SCC with a transmit data clock (CLK). For a typical setup, the clock is at X1 the data rate.
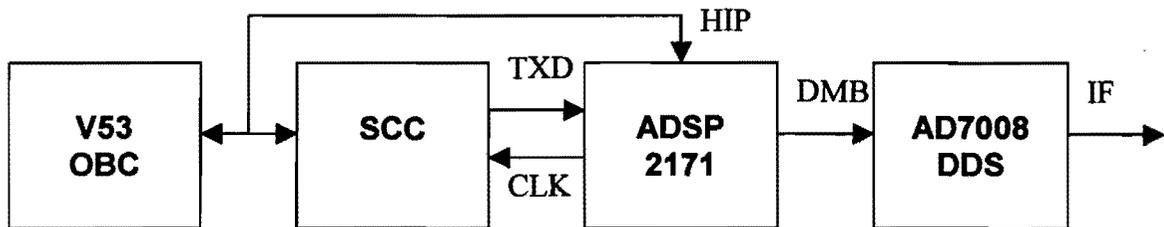
Figure 2 - Modulator Block Diagram

In addition to the serial data from the SCC, the DSP has a direct interface to the OBC via the Host Interface Port. This bus is used to load the executable DSP code, and can also be used for direct communication between the DSP and OBC. Even though this medium exists, it is not recommended for serial communication since the SCC is a much more efficient medium for that. The HIP is currently used for on-the fly programming of modulation parameters, and "I am alive" handshake signals.

The DSP generates a modulated signal using the Analog Devices AD7008 Direct Digital Synthesizer (DDS). The DDS includes a phase accumulator with a built in sin/cosine lookup table, Digital to Analog Converter (DAC), phase modulator, two frequency registers, and I/Q modulator. The DDS is designed to appear as a peripheral to the DSP. The DDS is fed from a 32MHz oscillator and can easily generate frequencies in the 10-12 MHz range. In order to implement different modulation schemes the DSP uses the built in FSK, Phase, and IQ modulators. The internal modulation registers can be updated at rates of up to 16.5MHz, so modulation techniques which would occupy the entire downlink bandwidth of AO-40 can be easily implemented. The different modulation options can be used in any combination desired.

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Demodulator DSP Design

The demodulator is based on three units. Those three units are a high speed Analog to Digital Converter (ADC), an Intersil HSP50016 Digital Down Converter (DDC), and a DSP. The demodulator configuration is shown in figure 3.
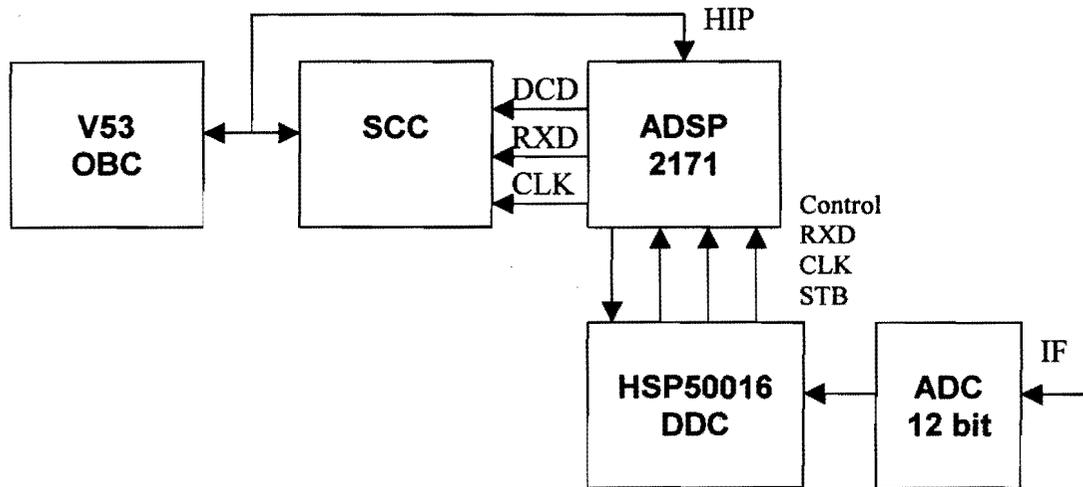
Figure 3 - Demodulator Block Diagram

    The ADC samples the IF at 32MHz. The resulting 12-bit word is fed into the DDC using a parallel bus. Even though the block diagram might suggest that each demodulator has its own ADC, there is only one ADC for all four demodulators. All demodulators are fed in parallel from this single ADC.

    Next in the processing line is the DDC. The Digital Down Converter is a sophisticated unit which converts sampled IF to baseband data. The DDC includes a complex (I/Q) signal generator, I/Q demodulator, high decimation filter, and Finite Impulse Response (FIR) filter. The features of this unit allow rather easy implementation of FM, PSK and AM demodulators. Its internal blocks could also be bypassed for combinational selection of features. This component has great potential for other applications such as a spectrum analyzer.

    The baseband data from the DDC is fed into the serial port (SPORT1) of the DSP. From there the DSP feeds the data to the SCC using a received data line (RXD), receive clock (CLK) and an optional data carrier detect (DCD). Just like the modulator DSPs, the demodulator DSPs also have the HIP for code loading and communications with the OBC.

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Code Design Process

Code design is based on the Analog Devices version 5.1 design tools. Up to a short while ago, those tools were available for free download from the Analog Devices web page. Unfortunately, this package has been removed, and new versions are no longer available free of charge. Due to this, it seems that this would be the package of choice for the foreseeable future. At the time of writing, the preliminary DSP software development kit is being put together.

The code generation process is illustrated in Figure 4. The two basic inputs to the design chain are the system architecture file, and the code file. The system architecture file describes the hardware configuration of the DSP for the rest of the chain to use. In it, the user defines the program, data, and IO memory map, and boot mode. Since the DSP architecture is fixed, little changes in this file between applications.

Code File   Architecture File

Assembler   **System Builder**

Object Code, Utility Files   System Configuration File

Linker

Splitter   Executable File, Utility Files

HIP File!
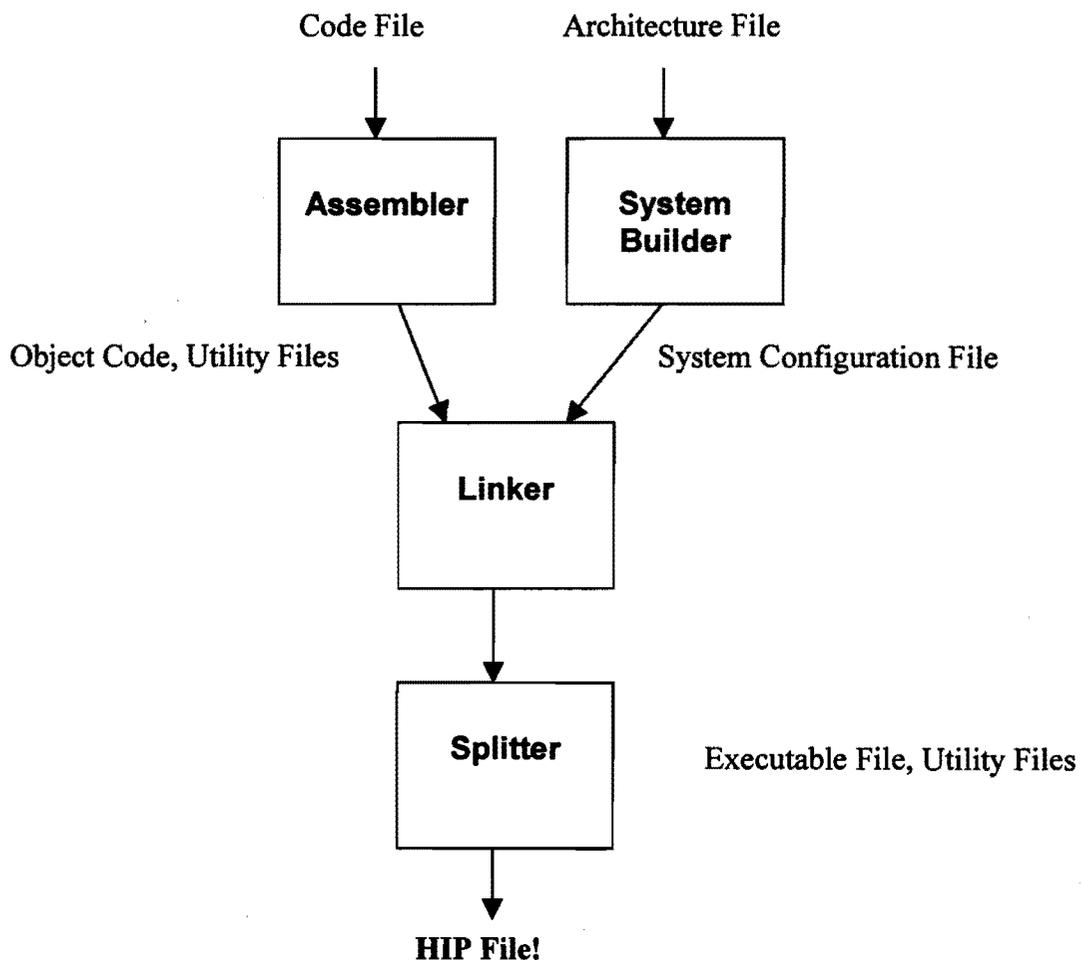
Figure 4 - Code Generation Process

The second and most important file is the code file. This is the actual DSP code program. Even though coding is done in assembler, the Analog Devices assembler is what I would refer to as assembly on steroids. It took many of the traditional assembly elements and turned them into a syntax more comparable to a higher level compiler. Due to this, coding is much easier, quicker to code, and even fun! The assembler will turn the DSP code file into an object code.

In addition to the object code, several utility files will be created. This includes a list file, initialization file, and code file. Linking is the next step in the process. Both the object code, and the architecture files are used to generate an executable. Again several utility files are created: map file, and symbol file. The last stage in the process is the splitter. The splitter turns the executable into a format which can be uploaded via the Host Interface Port of the DSP. In the end, we are left with one file in Intel format, which we upload to the spacecraft and run.

Even though this process might seem complex, it really is simple. The architecture file almost never changes, and the entire chain is invoked using a single batch file. No fancy integrated development environment is available, but the tools have been tested and known to work on Windows 98 and NT machines.

In addition to the design tools, a simulator is available. The main drawback of the simulator is that it only operates under DOS and will not work under Windows in a DOS window. Aside from that, it has proven to be very useful in code test before uploading to the spacecraft. Although the simulator cannot simulate the DDC and DDS, inputs and output can be simulated to a reasonable degree of confidence.

The fun part comes after the code has been compiled – testing on AO-40. The design cycle is shown in figure 5.
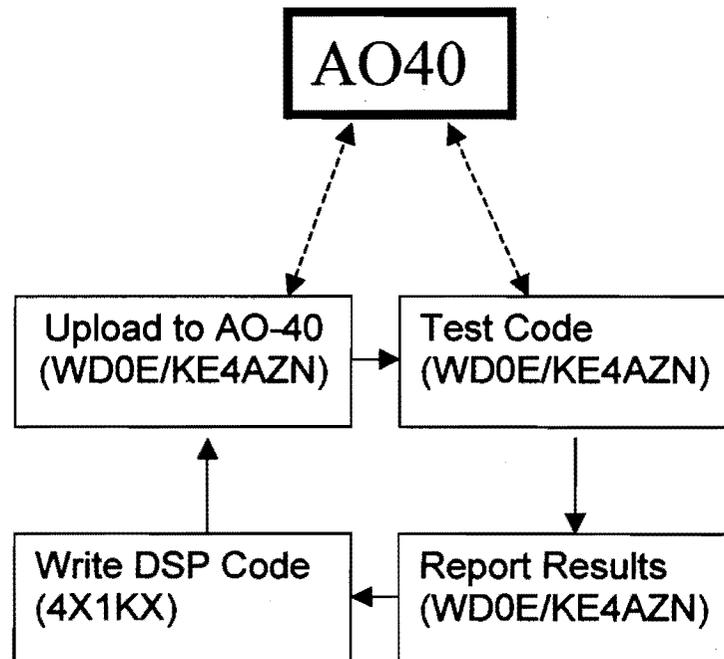
Figure 5 - DSP Design Cycle

The first step is code design. The concept is defined, and discussed with the RUDAK operator and system designer. Current support is provided by Lyle Johnson KK7P, Harold Price NK6K, and Jim White WD0E. Based on the decisions, code is written by Assi Friedman 4X1KX, and provided to the spacecraft operators via email, accompanied by a simple test procedure. Coding usually takes several days. At this point, both RUDAK operators Mike Kingery KE4AZN and Jim White WD0E check to see who has the first shot at it, and whoever it is – tests the code. A test includes uploading the code to RUDAK using WISP (microsat communications software by Chris Jackson), loading it to the appropriate DSP, and then checking for expected results. At the end of the session, an email is usually sent to report the results. Following this, the code is evaluated corrected, updated or redone. This cycle can take two days at best, with 4-7 days being more typical. All the code written up to present time was designed and tested using this design cycle.

RUDAK Emulator

Since the design cycle is so slow, the RUDAK team decided to design a DSP emulator. The design was done by Lyle Johnson and Assi Friedman based on input from the team. The goal of the design is to build a 100% RUDAK compatible emulator of one full DSP modem. The emulator will enable a DSP software writer to code and test on the ground before the code is ever uploaded to the spacecraft. This will greatly reduce the design cycle, and enable more people to participate in this effort. A block diagram of the emulator is shown in figure 6.
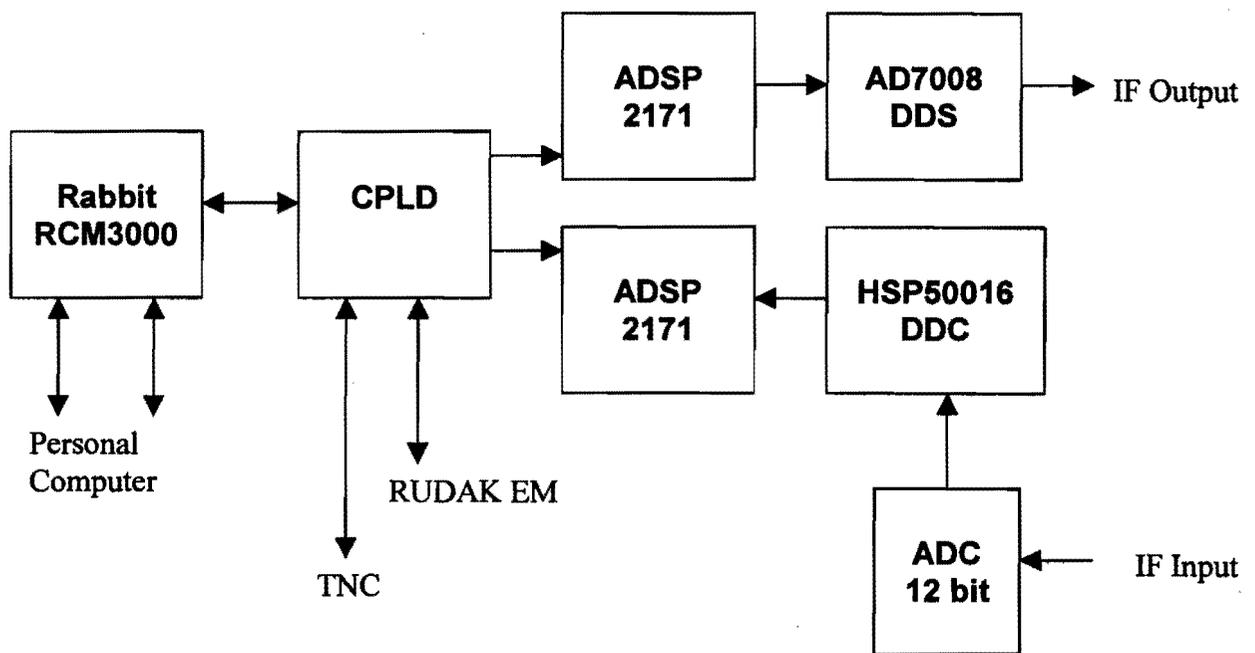
Figure 6 - RUDAK Emulator

Figure 6 is a slightly simplified functional diagram of the emulator, but the arrows illustrate the data flow sequence. The first feature of the emulator is that it includes one full DSP modulator channel, and one full DSP demodulator. The channels are 100% compatible replicas of the units on AO-40. Both modems are fed into a CPLD, which provides glue logic switching and conversion between the DSPs and the Rabbit RCM3000 processor board.

The RCM3000 is essentially an OBC replacement, and it provides two RS232 serial ports for hookup to a personal computer. The first serial port will provide the user with a loader and some additional debugging capability, and the second serial port will provide the user with a KISS TNC type connection, which will emulate the RUDAK's SCC. Additional plugs were added to allow the developer to connect the emulator to an external TNC, or a RUDAK EM board. The design detail will be made public so individuals interested in their own emulator can build it themselves. In addition, a policy for lending out the units will be solidified.

At the time of writing, the emulator design has been approved, a printed circuit board was designed by Chuck Green, and some of the parts have been acquired. The design has also been approved by AMSAT-NA, and hopefully by the time the AMSAT-NA conference takes place, more progress can be reported.

Current DSP Testing Status

The following is an update of currently available code for RUDAK DSPs. The team is making progress continuously, so it is expected that new progress will be reported at the AMSAT-NA 2002 conference

1. ZRO code: This application produces a fixed carrier on a preset frequency. The carrier begins the cycle at full DDS power. Then, the carrier power is reduced by precisely 3dB every 10 seconds down to –45dBc for a total of 16 steps. The cycle repeats it self automatically. This tool is strictly experimental and demonstrates a non-communications application for the DSP. This application was designed to assist users in obtaining an apples to apples comparison of ground-station receiver performance.

2. Siggen: This is a simple tool designed to assist AO-40 operators in testing the various downlinks. It enables the operators to generate a carrier on the downlink with on-the-fly capability to adjust frequency and power.

3. Modems: three modems are currently in works, 1200AFSK, 1200BPSK, and 9600FSK. All three modems now generate proper downlinks, but the link between the SCC and the DSP has not been proven yet. Once this is done, RUDAK will have functional downlinks operating in the three most common modulation techniques in amateur radio.

4. Multiple carriers: One of the first attempts to run several DSPs together to try to gauge the interaction of the hardware RUDAK downlinks and DSP downlinks at the same time. Four different DSP carriers were generated and the spectrum was monitored for inter-modulation.

As far as the RUDAK hardware, the downlink MOs have been the focus of testing. The functionality of the MO DSP and DDS has been verified to about 95%. The DEM units on the other hand are uncharted territory. Up to present time of writing, none of the hardware has been tested. It is expected that the development of the Emulator will help accelerate the testing of those units.

What's next to come?

From the description above, it should be obvious that the large flexibility designed into the DSP MO and DEMs will enable a lot of different applications to be written, and used. The best thing about it is that the ultimate application hasn't been discovered yet!
As brainstorming ideas here are some possibilities:
- BPSK, QPSK downlinks, variable rates
- Direct Sequence Spread Spectrum
- Forward Error Correction, convolution encoding
- Regenerative digital transponder
- Imaging: SSTV, APT, WEFAX
- Digital voice
- Spectrum analyzer
- Ranging system

Summary
DSP experimentation on board RUDAK began early May with the MO DSPs only. Up to this point, the downlink hardware is almost 100% proven, and confidence level in operating the DSPs is increasing with every program tested. At present, the RUDAK team is still focusing on testing the hardware and implementing traditional communications modems. In a parallel effort, the team is working on a DSP emulator, which will enable developers to design and test application code before it is loaded to AO-40. The team will also release a software development for individual interested in developing software for RUDAK DSP. Once the initial goals are fulfilled, the team will begin to use the RUDAK DSP for experiments of new technology. The team hopes to be able to make this a valuable and viable system for new and exciting ideas in Amateur Radio communications.

DSP References:

- Analog Devices DSP home: http://www.analog.com/technology/dsp/index.html
- Analog Device 21xx page:
  http://www.analog.com/technology/dsp/16-bit/index.html
- Analog Device Technical Library:
  http://www.analog.com/technology/dsp/16-bit/library.html
- Analog Devices 5.1 Development Tools:
  http://www.analog.com/library/dspManuals/legacy.html
- AD7008 DDS: http://products.analog.com/products/info.asp?product=AD7008
- Intersil HSP50016 DDC:
  http://www.intersil.com/design/parametric/productinfo.asp?pn=HSP50016JI-52
- AD9042 ADC: http://products.analog.com/products/info.asp?product=AD9042
- The book "ADSP Family User's Manual" is available at no cost on the web:
  http://www.analog.com/library/dspManuals/ADSP-2100_fum_books.html

RUDAK Reference:

- RUDAK Digital Signal Processing on AO-40, Lyle Johnson KK7P, *The AMSAT Journal*, September/October 2001, pp. 8-12.
- RUDAK pages on AMSAT's web server:
    a. www.amsat.org/amsat/sats/phase3d/rudak-u
    b. www.amsat.org/amsat/sats/AO-40/rudak/telemetry/
    c. www.amsat.org/amsat.sats.AO-40/rudak/
    d. www.amsat-dl.org/journal/adlj-p3d.htm

DSP Software and Examples:

- http://www.aerospacesoftware.com/order.html "Objective Real-Time Software with the ADSP Tool Kit, ISBN 0-9682655-3-7" contains the ADSP DOS-based software tools for $20.
- QEX ran a series of articles by Peter Andersen, KC1HR, on the HSP50016 and AD7008 to implement a software defined radio. See the following issues: March, 1994; November, 1994; February, 1995; January, 1996; August, 1996; September, 1997; September, 1998. These are all on the QEX:1980-1998 CD-ROM available from the ARRL.

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AO-40 RUDAK Description and Results

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Abstract

The AMSAT AO-40 satellite now on orbit contains several experiments controlled through a module called RUDAK. It is presently in an extended GTO orbit with an apogee of about 58,000 km. The primary mission of this satellite is to provide a platform for multiple communications transponders. The RUDAK module provides digital communications functions as well as serving as the controller for most of the experiments onboard. This paper focuses on RUDAK and the associated experiments.

The RUDAK module is capable of providing a wide variety of digital communications functions and includes dual processors, mass memory and a suite of hardware and DSP modems. It has connectivity to the transponders, main housekeeping computer and to the experiments onboard. To this point in the mission it has been exercised primarily as an experiment controller.

The experiments operated through RUDAK include:
- two cameras
- an equipment set for receiving and measuring GPS signals
- a radiation measurement experiment
- an experiment to measure HF signal characteristics
- two CAN bus temperatures measurement nodes.

Interesting and in some cases unique results have been obtained from the GPS, radiation monitor, cameras and temperature measurement nodes. The associated principal investigators are reporting details of those results independently.

This paper describes the RUDAK experiment control module, how it was designed and optimized for this mission, how it controls and interacts with the experiments, the software issues associated with this function, operational issues and successful experiment interaction achieved so far. A summary of the results from some of the experiments is included, with emphasis on the unique data. Information on those design and operational features that have worked well as well those that have provided challenges are included.

Introduction

AO-40 (known as P3d prior to launch) was designed and built by engineers from Radio Amateur Satellite Corporation organizations around the world. Members and groups from 11 countries contributed hardware and engineering. It was launched in November 2000 on an Arian 5 into GTO. Subsequently the orbit was changed to an extended GTO with a 1,100 km perigee and 58,600 km apogee where it will remain. A number of problem have risen and been worked by the controllers.

At present the satellite remains operational with U and L band uplinks and an S band downlink. A VHF band uplink is also occasionally in use. This satellite is the fourth[*] in the series of highly elliptical orbit satellites built by AMSAT. Its primary function is to carry linear transponders for communications use by Amateurs worldwide and it has been very successful in that mode. It also carries the RUDAK module for digital communications and control of a set of experiments.

Figure 1 - The P3d satellite undergoing final testing at the Arian launch site in Kourou. Shown is the antenna side of the satellite with two of the equipment bays visible. RUDAK is in the bay on the far side. Some of the GPS patch antennas may be seen around the edges of this surface. The two SCOPE cameras are on the far side behind and to the right of the engine bell.
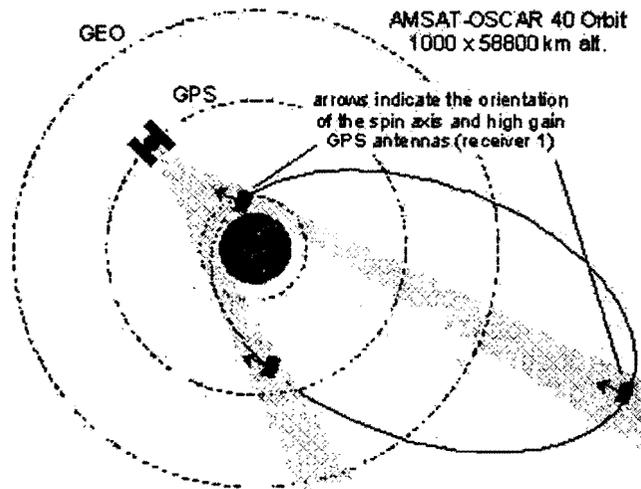

Figure 2 - The AO-40 orbit relative to the earth, GPS constellation altitude, and the GEO belt. Roughly to scale.

The RUDAK (Regenerativer Umsetzer fur Digital Amateurfunk Kommunikation) is an acronym in German roughly meaning digital regenerator of radio signals. The idea of a digital communications module with DSP units programmable in space on an Amateur satellite originated with Peter Gulzow about 12 years ago. That concept evolved into the very complex and capable module flown in AO-40.

To date RUDAK has not been made available for Amateurs as a store and forward digital BBS or as a digital repeater. Operations have focused on continued testing and exercise of the experiments. Operation of the GPS and CEDEX radiation experiments has progressed beyond testing to operation and data collection. The temperature nodes were found operational and some data has been gathered. The SCOPE cameras have been used to take some interesting pictures and software work to make their operations easier and faster continues. The Monitor unit has not yet been tested.

In this paper we first describe the hardware of the RUDAK unit and the software that runs in it. We then describe each experiment RUDAK controls and discuss operations to date. In the section on the operation of each experiment we have included some results, however the detailed results and data analysis are deferred to the principal investigators. We conclude with a summary including plans for the future. Acknowledgements, a contact list and notes appear at the end.

RUDAK Hardware Description

The RUDAK hardware is designed to provide flexible communications links for the experiments it supports. It is not designed to be a spacecraft control computer, so does not provide complete loop load management. Indeed, RUDAK as implemented on the AO-40 spacecraft lacks the ability to turn its experiments on or off.

Since the focus of this paper is experiment support, the communications facilities of RUDAK will be briefly presented, then the specific design decisions made for experiment support will be described.

RUDAK System Overview

RUDAK consists of a pair of V53-based (x86 compatible) CPUs. Each CPU has 16 megabytes of Error Detecting and Correcting (EDAC) memory. The 16 megabytes is what is visible to the processor - it is composed of 24 megabytes of physical memory. Memory is organized to be byte addressable and accessible, with single-bit-per-byte error correction. The memory system is 16 bits wide.

The main mission of RUDAK is communications. Therefore, each processor has five (5) dual channel multi-protocol serial communications controllers (SCC) supported by 16 channels of DMA. Associated with each processor there are four (4) DSP-based modulators and four (4) DSP-based demodulators, two (2) hardware-based 9600 bit/sec FSK modems, and one (1) 153.6 kilobit/sec PSK modem.

There are multiple experiments depending on RUDAK for data and program information. RUDAK's two CPUs have a high-speed parallel FIFO interface to enable them to share data quickly. Each CPU also monitors the state of the other, so if one fails and loses power, for example, the other can run all the experiments.

Experiments Supported

In addition to its basic analog communications payloads, AO-40 has a radiation monitor (CEDEX), numerous temperature sensors on a distributed network (dubbed Smartnodes on the CAN-LAN), a pair of GPS receivers with multiple antennas for attitude determination (Trimble units, modified TANS-Vector), an HF scanning receiver (MONITOR) and a pair of color CCD cameras (SCOPE).

Experiment Power Control

The AO-40 spacecraft contains many varied payloads. The primary spacecraft computer, called the Integrated Housekeeping Unit (IHU) is tasked with managing the overall spacecraft. Drawing on a long heritage of successful space operations, it is an updated version of a design first launched in 1980. It is based on the Sandia rad-hard version of the venerable RCA CDP-1802 COSMAC processor. It runs a threaded interpretive language called IPS, which is very FORTH-like.

The IHU is very limited in its computation speed, and its data links with the spacecraft command stations run at only 400 bit/sec.

For these reasons, the IHU was not considered suitable for interacting with and running the various experiments mentioned above. However, the IHU is tasked with spacecraft safety and power management, so it directly asserts ON/OFF control on all experiments.

Since it is vital that RUDAK know which experiments are currently active, the IHU outbound telemetry link, which includes status frames telling the state of all payloads, is tapped and monitored by RUDAK, using specialized logic burned into FPGAs.
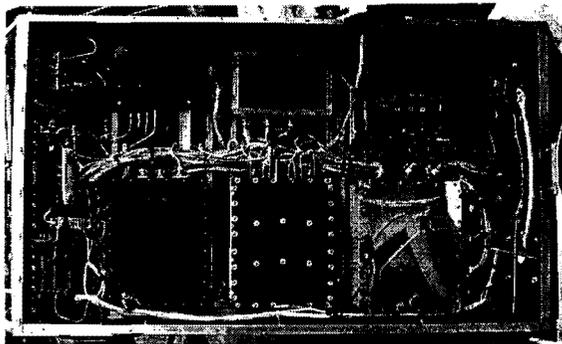
Figure 3 - RUDAK is in the center lower module in this equipment bay on the perimeter of AO-40

Experiment Interfaces

CAN Bus

SCOPE, the HF scanner, the Smartnodes and CEDEX are connected on a CAN bus. CAN (Controller Area Network) was originally developed for the automotive industry to reliably transport sensor data and actuation commands with deterministic latencies. It has very small data payloads (8 bytes maximum). On AO-40, it operates at a signaling rate of 1 megabit/sec.

The Smartnodes, the HF scanner and CEDEX have relatively light data requirements, so the CAN bus works quite well for them.

There was considerable concern about the reliability of the CAN LAN in a high orbit, so great care was exercised in choosing the ICs for it. Further, since the Smartnodes would not have EDAC systems, they were designed to hold data for short periods of time to minimize corruption. Program information is stored on fusible link CMOS PROMs. The micro controller chosen was all-CMOS with no EEPROM cells used in its configuration. After nearly 18 months on orbit, they are performing well.

SCOPE Backup

SCOPE has a backup communications path in the form of an RS485 link. This is a 5V differential signaling system using standard asynchronous data format. Both SCOPEs listen to the outbound link from RUDAK, and the addressed camera responds on the paralleled inbound link. The drivers are tri-stated unless active.

Each SCOPE camera has two such ports, and each RUDAK CPU has one, so a failure of a RUDAK CPU

along with the failure of the CAN LAN will still allow SCOPE to function.

GPS

The GPS receivers were not designed specifically for this mission, and lack both a CAN interface and tristate async drivers. Each receiver has a primary and a secondary port, however not all information can be passed over the secondary port. Further complicating the interface is the fact that only one serial port was available on the RUDAK processor board at the time GPS receivers were chosen. A method had to be developed to talk to a pair of GPS receivers on one port.

The solution was multi-faceted. First, differential RS422 signaling was used to maximize reliability at the physical layer. Each RUDAK CPU has a dedicated pair of RS422 receivers, one to the primary port of one of the GPS receivers, and the other to the secondary port of the other GPS receiver. Likewise, dual differential drivers are incorporated, connected to the same ports. These drivers are NOT tri-stated.

The RUDAK CPU selects which port it will drive, and which it will listen to, on its single available serial port.

There is a further problem in that the IHU had a single power control line available for both GPS receivers, but it makes sense to generally operate only one at a time due to antenna placements and the high power consumption of the receivers.

The solution was to make a special control board that allowed RUDAK to assert control **in series** with the IHU. Thus, the IHU can force both receivers OFF, but a receiver will only come ON if both the IHU and RUDAK command it. Of course this is further complicated by the fact that a RUDAK CPU might fail and with it the power control over the GPS receivers.

This part of the solution was implemented by using exclusive-or (XOR) gates for power commands, and monitoring the state of each GPS power switch. Each CPU has a control line to an input of each of the two XOR gates. If one CPU fails, the other CPU can still exercise positive power control over both GPS receivers.

The XOR gates are 4000-series CMOS, proven reliable in this orbit over many years on previous AMSAT missions. The schematic below details the power-switching scheme. Note that the XOR gate is powered as long as either RUDAK CPU has power. +10V is the primary power to the entire RUDAK chassis - if it fails, RUDAK is lost.

RUDAKII BLOCK DIAGRAM
Simplified. CPU A.
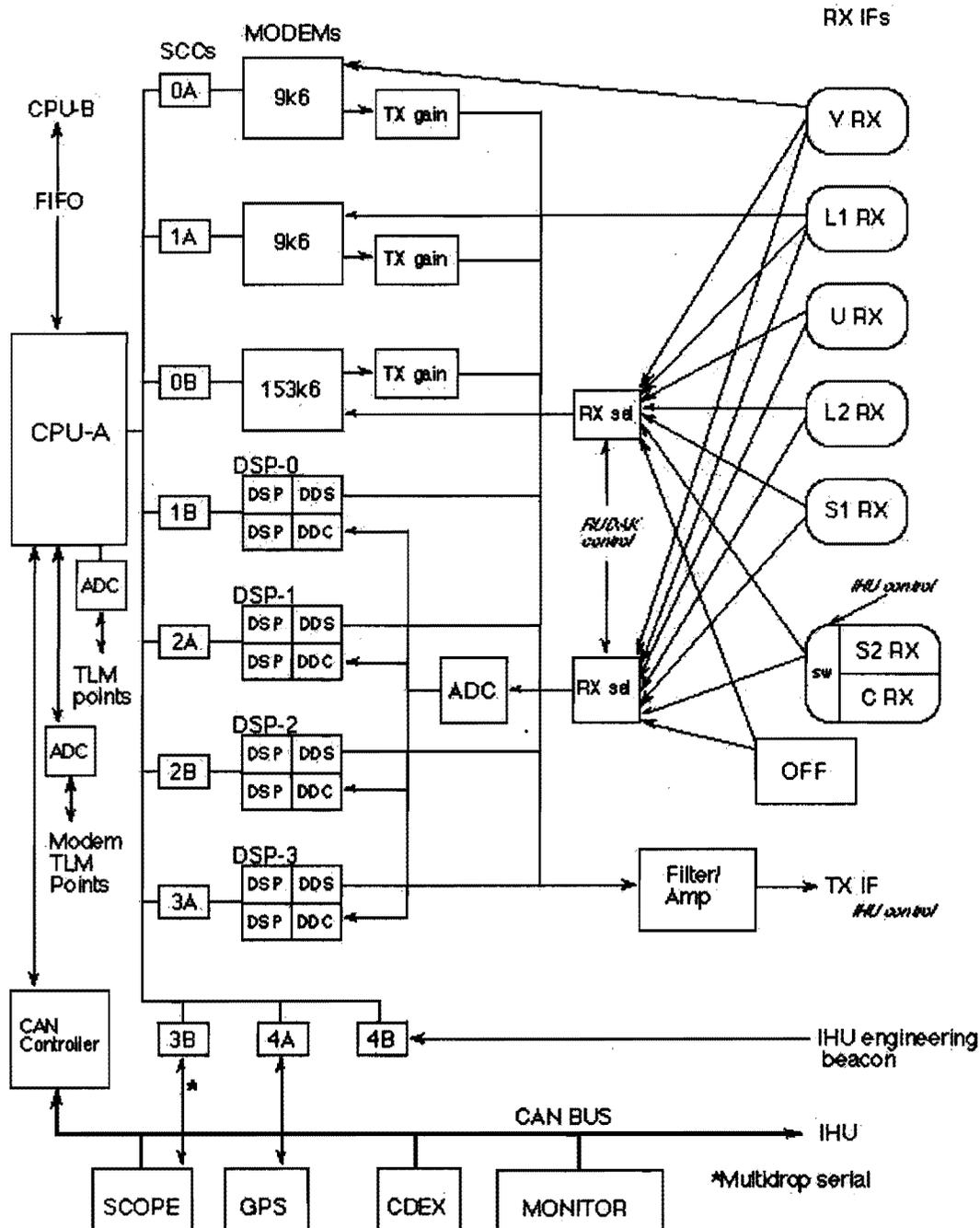
Figure 4 - General block diagram of RUDAK and interconnected hardware including the experiments and communications equipment

Software

RUDAK uses the Spacecraft Operating System (SCOS) from BekTek, Inc. SCOS is a pre-emptive dispatch multi-tasking operating system optimized for use with the 80186 family of microprocessors. RUDAK is based on an NEC V53, object code compatible with the 80186. SCOS includes I/O drivers, data transfer

protocols, and file systems designed for use in low earth orbit. SCOS has been flown on 28 spacecraft to date, with several more in various stages of construction.

General SCOS Discussion
SCOS is a child of the mid-1980's. Its origins were as a software development platform for a multi-tasking I/O card for the IBM PC in 1986. The goals of that product[†] were equally valid in the low cost spacecraft development world, allowing a "DOS" programmer to:

- Write applications without the need for in depth understanding of the hardware architecture.

- Write applications for a multi-tasking environment while paying as little attention to the multitasking environment as possible.

- Access serial I/O devices through SCOS streams and I/O drivers.

- Write applications in the C language.

- Include most standard C library functions in tasks.

The most important attributes of SCOS were that it :

- Had a very small footprint

- Allowed uploading of new tasks (programs) without affecting the rest of the running programs

SCOS was first posited at a fast food restaurant during a digital communications conference, when a software developer was seated between two groups of spacecraft computer designers. Both groups were looking for a small-footprint operating system that would allow fast development of sophisticated software. One group would launch the AMSAT microsats, the other UoSAT-3. It was agreed that a commercial package would be ported for both groups use, provided each used the architecture already supported by that package – 80186 CPU and Intel 8030 SCC. In only few weeks, both spacecraft groups had diverged, one to V40 and NEC 72001, the other to 80186 and an 8530 SCC. Each had a different mass memory access method. This led to an important design rule – keep any knowledge of spacecraft hardware particulars (expect for Vxx/80x86

differences) out of the operating system and firmly in the user domain.

This led directly to the kernel and "everything else" design. The kernel knows only about the CPU, primarily different hardware timer architecture. Everything else is a separate executable – a .EXE file in DOS parlance or a "task" in SCOS-speak. This led to a kernel that needed only minor changes from one hardware platform to the next, and it has therefore been very stable, running for more than five years in one case[‡] without a crash or reload.
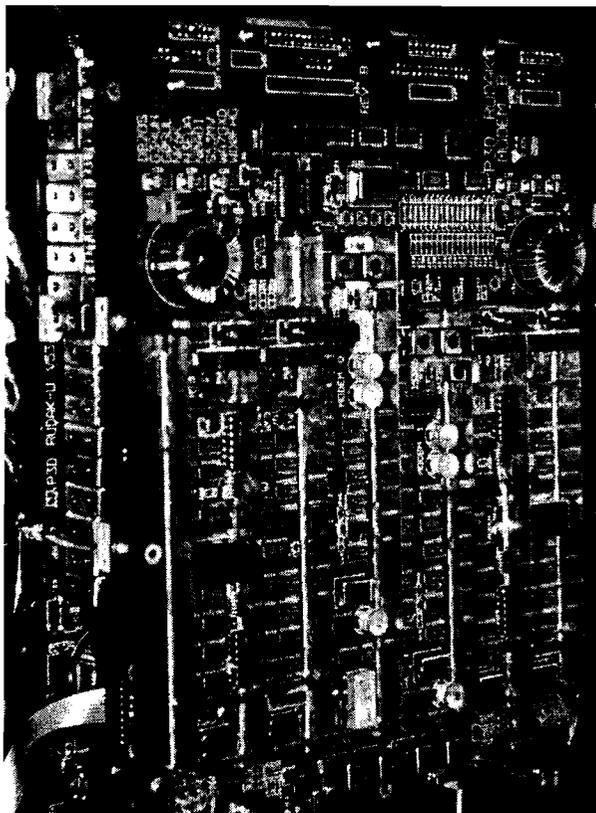

Figure 5 - RUDAK board stack under test
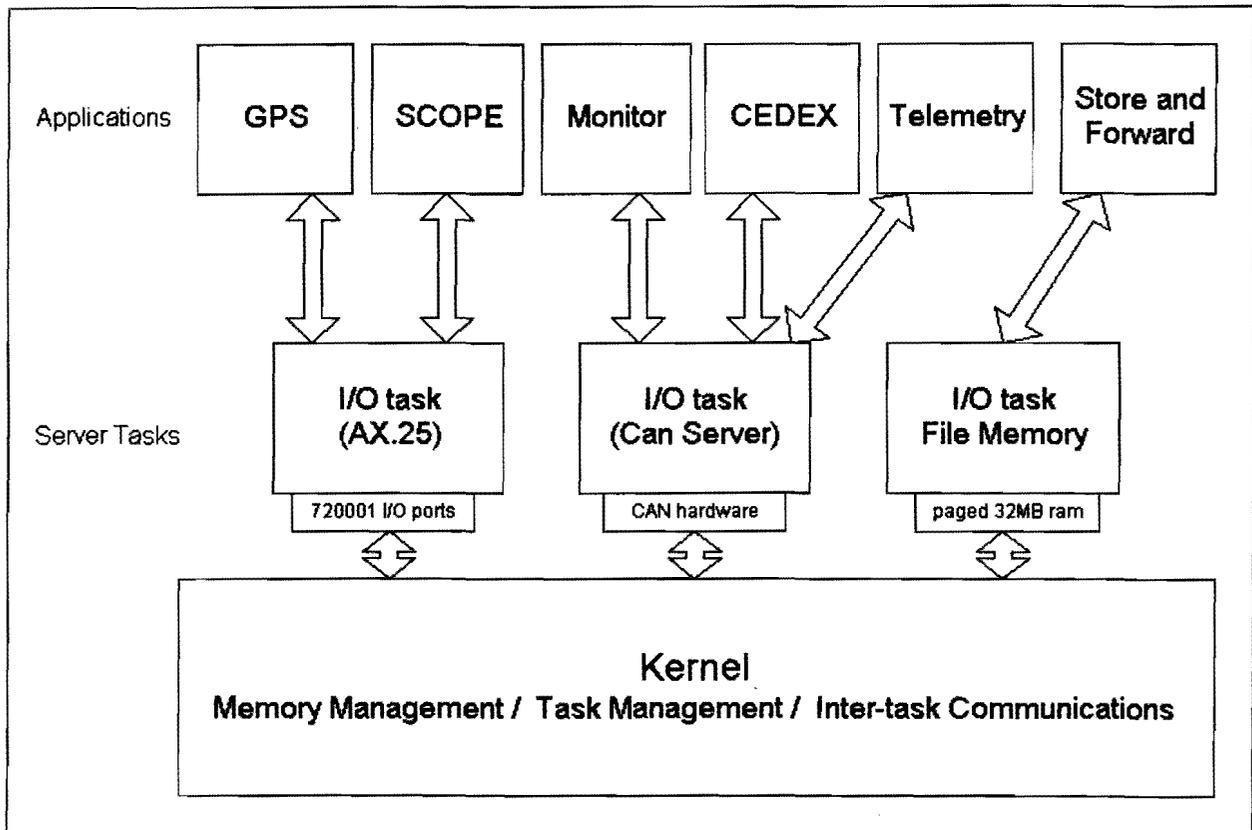
Figure 6 - Each of the non-kernel tasks can be uploaded on the fly[§].

The kernel's only job is to timeshare tasks, dole out memory on request, and provide a means where one task can send messages to another. On RUDAK, there are several tasks not shown in figure 6, including tasks for the CEDEX and MONITOR experiments, and a task to load software into the DSP modems.

In particular, I/O drivers were kept out of the kernel. In cases where a single software task owned a port, as in the case of the serial port to the GPS receivers, the I/O driver was linked directly with the user task. In the case of a shared facility, such as the CAN bus or the HDLC downlink ports, where several tasks need access, a server task is built. The server task uses the SCOS inter-task communications method called "streams"[**] to exchange data with user tasks. The author of a server task typically provides an interface library that is linked to user tasks, and communicates to the server task via stream. The file system server task, the CAN server task, and the AX.25 protocol task all provide interface libraries in the model shown in figure 8.
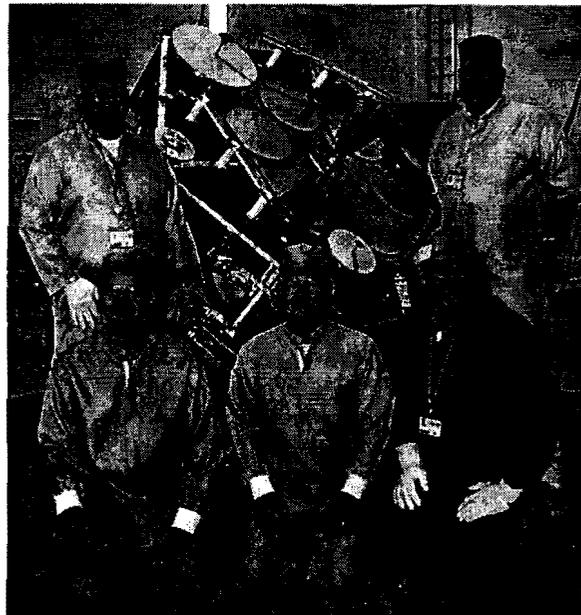
Figure 7 - Part of the RUDAK team in Kourou: Left to right Peter Gulzow, Chuck Green, Jim White, Lyle Johnson, Bdale Garbee.
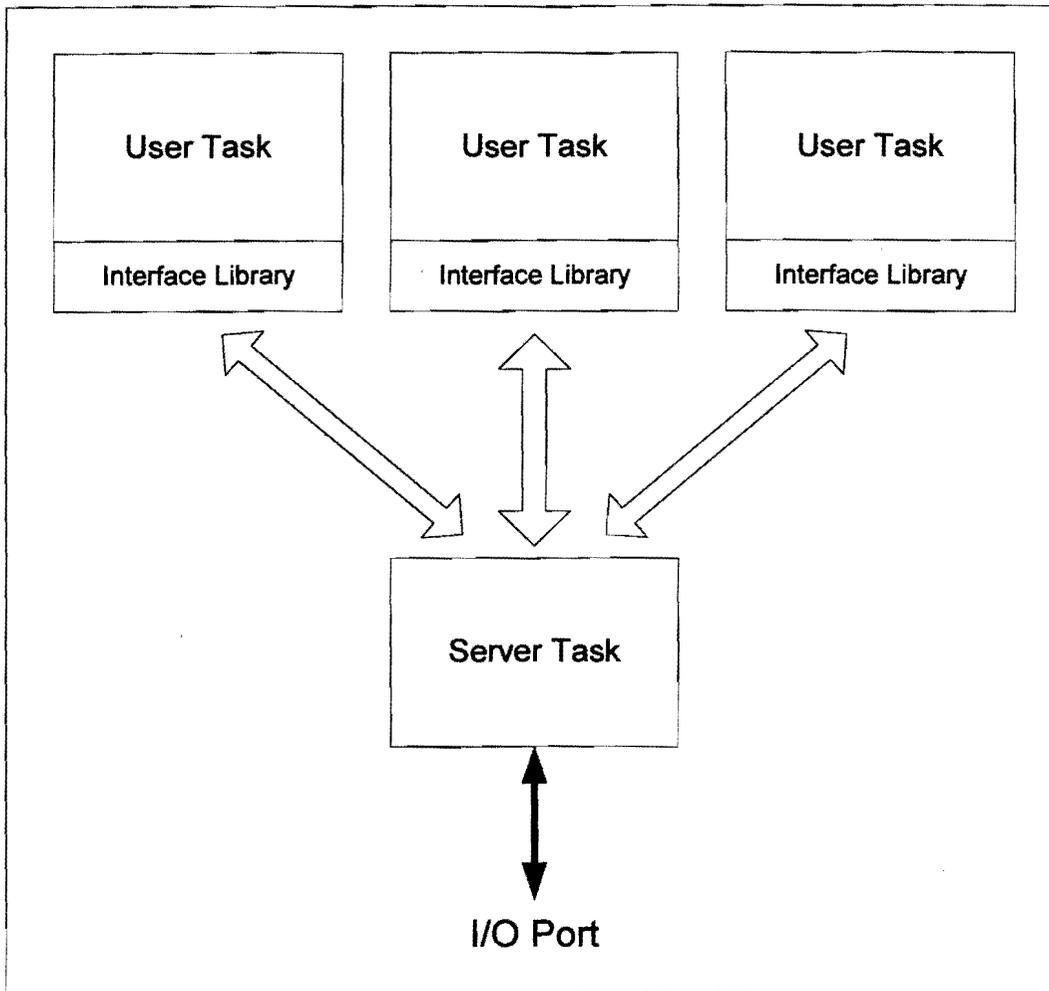
Figure 8 - Server task model

All those tasks are a good thing – it leads to modular software design, and easily replaceable components. In RUDAK, each task has its own AX.25 call sign, and a ground station can individually access a particular task. There is no common message handling or downlink muxing point, each task talks to a peer or peers on the ground. This scheme has worked well for the types of spacecraft that use SCOS. They tend to have a large number of experiments run by different organizations in a company or completely different user organizations. While some interaction between groups is necessary, the less interaction required, the better.

One other hallmark of SCOS spacecraft is their tendency to rely on the file system as an intermediary between experiments and the ground. Small low cost spacecraft tend toward LEO, which limits the access time per orbit to 10-15 minutes, and a small number of passes per day. Complex experiments get their marching orders from "script" files that are uploaded in advance of need. Results, such as GPS data, radiation data, long duration telemetry, images, etc. are placed in files. A common file download facility is then used to recover the files and delete them once they are downloaded.

As the file system task[††] and its attendant user interface offer fopen/fclose/fwrite/fwrite C library calls, large portions of the script and data storage elements of a task can be tested using desktop development tools in an environment familiar to the user.

Multitasking and task loading

For any but the most trivial of tasks, we view multitasking as a far better alternative to the "everything in a big loop" design. While highly time dependent real-time control tasks might not fit the model, most of the tasks undertaken by this class of spacecraft can accommodate a preemptive dispatch scheduler. Complex attitude control and orbit control, as demonstrated by SSTL's Uo-12 spacecraft were performed on an SCOS platform.

SCOS tasks are event driven – they sleep in non-executing state until some event occurs, a message is received, a timer goes off, or an I/O operation is completed. Compute bound tasks are preempted on a 100 millisecond timer.

Tasks can be uploaded at any time. Tasks are compiled using a Microsoft 16 bit complier, and link into a relocatable .EXE image. A user task on the spacecraft handles the loading process in concert with a peer program on the ground. The ground program sends the size of the new task to the spacecraft loader, which gets memory from the kernel. The address of this memory is sent to the ground program, which then relocates the .EXE file to run at that location. The resulting binary is sent to the loader task, which copies the task into memory. Finally, the loader tasks signals the kernel to start the new task executing.

SSTL has written a facility that can take a .EXE file from the onboard file system, relocate it, and load it, all onboard. This is useful when a task needs to run only occasionally, or for faster reloading after a crash.

Many spacecraft in this class tend to be in a near constant state of software development. Some are training missions, others are on a short development cycle where the experiment software is written after launch. Others are hardware development missions where new algorithms are being tested. In keeping with the low cost nature of these missions, testing is done "in situ", meaning in space. Due either to time constraints, or cost constraints, or both i.e., launching the only prototype, fresh software can sometimes crash. RUDAK, as with the other 16 bit 80x86 systems, does not have memory protection of one task from another. Misbehaving software can sometimes take down the entire system.

Almost all of the spacecraft that use SCOS have depended on a simple ROM-based bootloader. The SCOS kernel and a more complex loader are uploaded using the ROM bootloader. The other tasks are then loaded from the ground, or from onboard RAM. Again keeping costs low, file storage space is usually not hardware EDAC protected, it is instead protected with software block codes like RS. A file-based reload must occur before enough errors occur to swamp the ability of the block codes to correct the errors.

RUDAK Specifics

RUDAK and the AO-40 spacecraft was an ambitious (possible over ambitious) project. An amateur radio project differs from some commercial projects in the amount of testing that can be done, and the amount of software that can be developed. It is difficult to sustain interest over the several years (nearly 8 in the case of AO-40) that a project of this magnitude that take. AO-40 and RUDAK contain many operational modes and combinations of modes that were never tested, for example, interaction between the analog users and digital users in the same transponder. Software for the DSP modems, beyond simple hardware tests, has not been developed. RUDAK, which is two near identical independent modules (two V53s, two 32 MB ram disks, two sets of 8 HDLC I/O ports, two sets of 8 DSP

processors) have outstripped our volunteer ability to produce the requisite application software. Next time (we promise each time) less is more.

Still, a substantial effort has gone into the project, with gratifying results.

CPU

The full complement of SCOS software and standard AX.25 and file transfer software developed for previous missions was ported to RUDAK, which was then used as the basis for other V53 projects for Canada's MOST mission and several spacecraft from Spacequest.

Telemetry/Control

The standard AMSAT telemetry module, originally developed for AO-16 in 1989 was expanded and ported for use on RUDAK

CAN

Server software for the CAN bus, supporting applications for SCOPE, CEDEX, MONITOR, and various CAN-attached telemetry modules, has been used to gather data from all modules but MONITOR. MONITOR awaits the deployment of the solar panels.

GPS

Data has been gathered from both GPS receivers through the 9600 baud serial ports. The GPS data, including raw receiver data and algorithmic output, is regularly stored in the file system and downloaded. In addition, a pass through real-time mode has been used to directly connect a standard diagnostic software package on the ground to the space based GPS receiver. GPS data is encapsulated in AX.25 packets and sent to a TNC (HDLC to serial converter) on the ground.

SCOPE

Using both a serial interface and CAN, the SCOPE task communicates with a bootloader in the SCOPE camera to load software into the camera controller and store received images into the RUDAK file system for later download.

Ground Software

The initial software load is accomplished from the ground using a program specifically designed to interact with the ROM based boot loader in each RUDAK processor. Once the SCOS kernel and an initial housekeeping task have been loaded the kernel takes over memory management and another program on the ground is used with the smart loading in the housekeeping task to load the AX.25 stack and the full-up housekeeping task. That housekeeping task also includes the smart loader. At this point full telemetry and control of the RUDAK hardware is available. Generally the file system is loaded next because its capabilities are used by the tasks that run experiments.

At this point individual tasks that work with each experiment may be loaded depending on the objectives. For example the SCOPE camera task may be loaded. SCOPE is an example of an experiment that must have software loaded into its computer from the ground. For SCOPE and similar experiments a binary image of the experiment software is uploaded to the file system. The SCOPE task is commanded to move that software into the camera processor and execute it. The SCOPE task is then commanded from the ground to set parameters in the camera, take pictures and move them to the file system, etc. Once a picture is in the file system it may be downloaded and post processed.

A single command program is in use on the ground to send all commands to all experiment's tasks and the housekeeping task. That program also decodes and displays telemetry from the RUDAK module. In some cases a reduced function version of that command program has been provided to the experiment builders so they can control their experiment directly.

What's next

A few refinements are in store for RUDAK software. These may include on board compression of data to compensate for a less than expected link margin and on board filtering of redundant GPS data. Further DSP modems may accommodate other data rates and be used to further investigate link margins. Because virtually all software is loaded from the ground great flexibility is possible. The housekeeping task has been modified several times since launch to add functions and fix minor problems. The software that runs in the SCOPE camera and the SCOPE task are presently being modified to compress the images in the camera and allow scheduling of photo sessions.

GPS Experiment

The GPS experiment on AO-40 was provided by the GPS group at the NASA Goddard Space Flight Center. It consists of two Trimble TANS Vector receivers, each with its own set of four antennas. The system is designed to provide experimental attitude determination as well as self generated Keplarian elements after the satellite is in three axis stable mode and the antenna side of the satellite is kept pointing at the earth. The GPS antennas on the side of the satellite containing the communications antennas have about 10dB of gain and a beam width designed to cover the earth and the GPS constellation when AO-40 is at or near apogee. They are connected to one of the receivers, referred to as the 'A' receiver. The other antenna set is on the opposite surface of the satellite and is connected to the 'B' receiver. These antennas have less gain and a broader beam width and are designed to receive signals when

the satellite is near perigee and under the GPS constellation. The TANS Vector is capable of providing self generated Keplarian elements as well as attitude information in roll, pitch and yaw.

The objectives of the experiment are:
- Attempt to obtain a fix and generate Kep sets from each receiver when in the part of the orbit it was designed for.
- Measure and report on various GPS signal values from all parts of the orbit, but particularly from or above geosynchronous altitude.

Each receiver has two serial communication ports. One of these is connected through a switch to each of the RUDAK processors via a 72001 serial communications controller integrated circuit (SCC). Through that switching arrangement each RUDAK processor can control which GPS receiver it is talking to. To save I/O pins in the RUDAK unit, the switching is controlled using the hardware flow control lines from the SCC. With this arrangement each RUDAK processor can talk to each GPS receiver providing flexibility and redundancy at little cost. The communications links are 9600 bps serial and the proprietary binary Trimble protocol is used.

Operations

The receivers were initially turned on in September of 2001 and were found to be working. In late September an operational session was held during which the GSFC investigators talked the RUDAK command station through a number of tests that proved various functions were working properly. At this point the satellite was at about the altitude of the geo band. GPS signals were first detected during this session.

Logging of data commenced in late September and continued intermittently for about 30 days. The software running in RUDAK under SCOS logs data in 1 hour time blocks. During that period about 10,000 Mb of data was collected, downloaded, and provided to the experimenters. A good deal of data logged in RUDAK was not downloaded because the file size indicated no satellites had been head during that time period.

These data have been analyzed by the GPS group at GSFC and the full results have been reported elsewhere. A summary of the results is presented below.

Results

Although the GPS receiver was not initialized in any way, it regularly returned GPS observations from points all around the orbit. Raw signal to noise levels as high

as 12 AMUs (Trimble Amplitude Measurement Units) or approximately 48 dB-Hz have been recorded at apogee, when the spacecraft was close to 60,000 km in altitude. On several occasions when the receiver was below the GPS constellation (below 20,000 km altitude), observations were reported for GPS satellites tracked through side lobe transmissions. Although the receiver has not returned any point solutions, there has been at least one occasion when four satellites were tracked simultaneously, and this short arc of data was used to compute point solutions after the fact. These results are encouraging, especially considering the spacecraft is currently in a spin-stabilized attitude mode that narrows the effective field of view of the receiving antennas and adversely affects GPS tracking. Already AO-40 has demonstrated the feasibility of recording GPS observations in HEO using an unaided receiver. Furthermore, it is providing important information about the characteristics of GPS signals received by a spacecraft in a HEO, which has long been of interest to many in the GPS community. Based on the data returned so far, the tracking performance is expected to improve when the spacecraft is transitioned to a three axis stabilized, nadir pointing attitude.
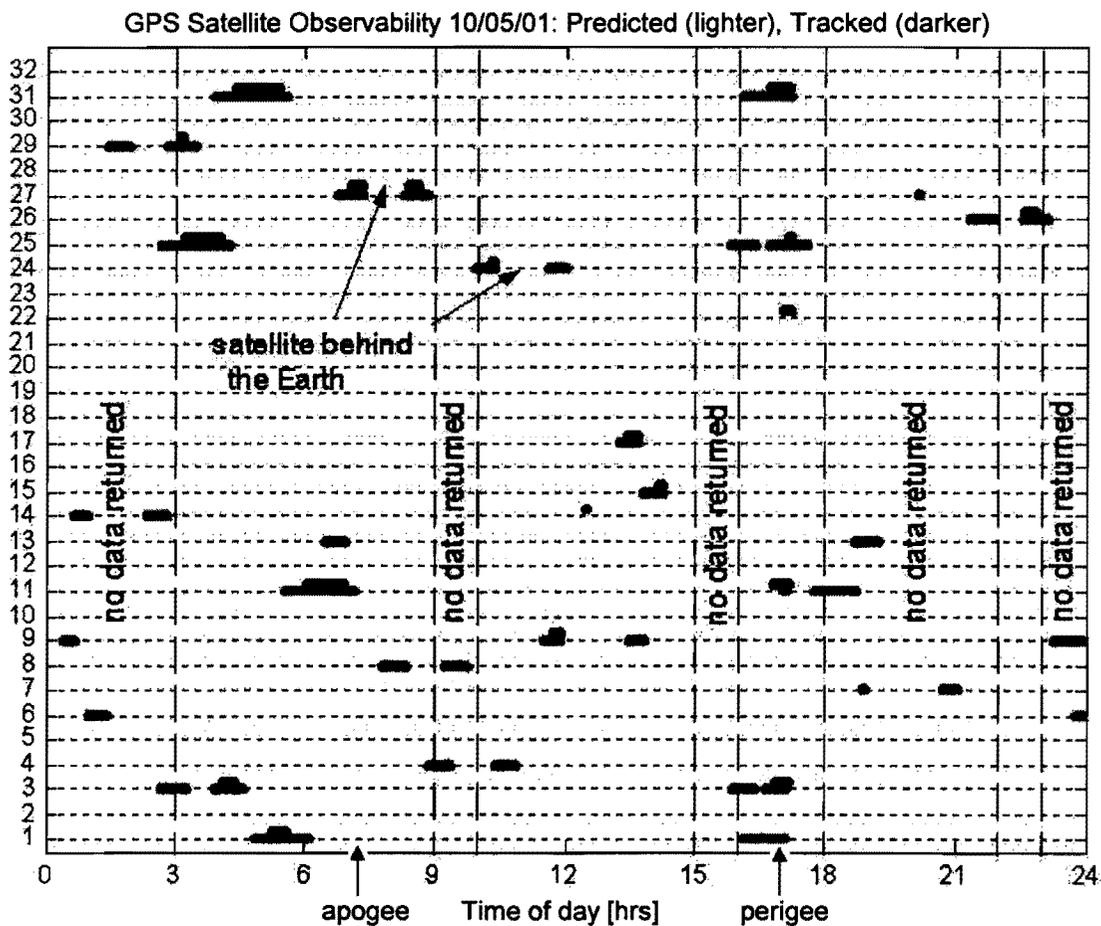

Figure 9 - Comparison of predicted GPS visibility and actual satellites tracked on 5 October, 2001, showing typical tracking performance of receiver and data outages
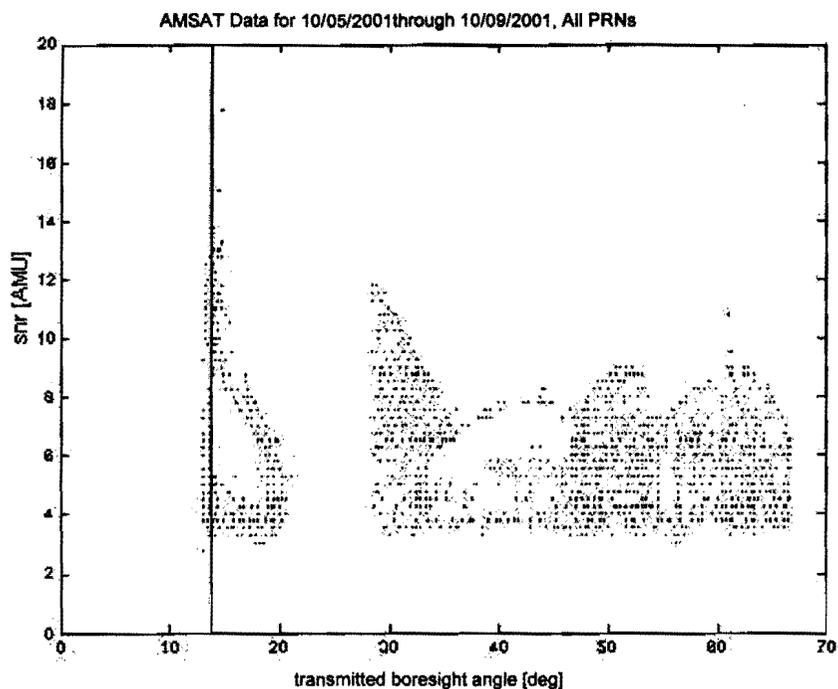
Figure 10 - Raw GPS signal levels plotted versus transmitted boresight angle.

Issues

Initially the complex method for switching a single SCC serial channel between the receivers using the flow control lines proved time consuming to work out in software. However it has worked flawlessly since. In this case only one software task needed to know how to exercise the switch so no driver was necessary.

During development there was some concern the amount of data from these receivers at 9600 bps would be difficult for the RUDAK processor to handle along with other tasks. To this point that has not been a problem. We have run the SCOS kernel, the AX.25 protocol stack, the housekeeping task, the two tasks that make up the file system, and the GPS task continuously for several weeks without difficulty, while logging tens of megabytes of data to the file system. At one point we also ran the CEDEX experiment task, again without difficulty. We believe that parsing the tasks between the two RUDAK processors will allow full operation of all the experiments simultaneously in the future.

The RUDMON program on the ground along with the ability of the SCOS GPS task to pass raw TANS command and diagnostic data to and from the GPS receivers has proved particularly successful. Every time that software has been used commands and data have flowed between it and the GPS receivers flawlessly. To the user (in this case the RUDAK

command station) that software gives the appearance of sitting at an ASCII terminal talking directly over a wired link to the TANS. This capability has made it possible to fully exercise all options of the TANS receivers and obtain instant diagnostic data. In fact it was during one such session that we first saw the apogee receiver hear a GPS signal and begin reporting its parameters.

A second data collection session was held between about 15 May and 15 June, 2002. During this period the apogee receiver was used to collect data nearly continuously. The perigee receiver was used during the final few days. Several additional MB of data were collected during this session. Analysis is ongoing.

SCOPE

SCOPE is an acronym for "Spacecraft Camera experiment for Observation of Planets and the Earth".

Objectives

The SCOPE experiment has the following three objectives.

- Taking full color pictures of the earth from high altitude orbit. Although there are several amateur satellites that have CCD cameras on board, most of

them are monochrome and in low earth orbit. SCOPE is intended to show us the image of earth floating in space in real color just like astronauts saw from Apollo on their way to the moon.

- Supporting satellite's attitude control as an Earth sensor. The AO-40 satellite has capability of controlling its attitude with its 3 axis attitude control system that makes it possible for the satellite to look down at the earth at any desired angle. The SCOPE camera can serve as an alignment tool for this attitude determination system or may serve as a backup system.

- Evaluate SCOPE as a sensor for the flight guidance system. JAMSAT has a plan for an amateur satellite that will fly from the earth to another planet. Traveling from planet to planet requires a flight guidance sensor called a star tracker. The SCOPE camera is capable of seeing relatively bright stars and this capability may make it useful as a star tracker. SCOPE is also able of capturing the image of a destination planet. This capability of the SCOPE camera will be evaluated with the Phase-3D project.

Hardware

Two individual cameras Camera-A with a narrow angle lens and Camera-B with a wide angle lens are housed in a single module case .

The size of module case is 297(D) x 227(W) x 130.6(H) mm, the mass of the SCOPE module with its two cameras is 5.4 kg.

The electronics system consists of four sections, CCD head, CPU, Memory, A/D converter and Power Supply.

The cameras each use a 3 CCD head from a PAL standard camera used in the industrial image processing field. This CCD head consists of a dichroic mirror to separate the colors and three inter-line transfer CCDs for red, green and blue. Specification of the CCD is as follows:

Image Circle = 1/2 inch
Pixels=752(H) x 582(V)
Pixel Size=8.6(H) x 8.3(V) micron

These CCD heads are commercially available as spare parts for an industrial grade PAL standard camera and were modified to be driven directly from the CPU.

Commercial off the shelf zoom lenses which were designed for the CCD head were employed. The zoom is not adjusted in space but was set before launch to a specific focal length determined by a study for obscuration from a nearby object (V band antenna) on the spacecraft and the viewing angle from the final orbit. The two cameras have the same zoom lens with different zoom ratio settings to provide narrow and wide view angles.

The front clear aperture of the lens is 41.5 mm, and the planned field of view (FOV) of Camera A is 16 degrees and FOV of Camera B is 32 degrees . ND (Neutral Density) filters were be used to adjust for the relative brightness of the earth. Three filters each with x4, x8 and x8 factor are employed for both optics providing x256 factor number. Those ND filters and hood are modified commercial products.

The lubricant used in commercial lenses could evaporate causing fatal contamination. The flight lenses were taken apart, cleaned and reassembled using space grade lubricant. The focus is adjusted to a vacuum environment by taking the difference in refraction into account.

From 4000km these FOVs give following calculated resolution of objects on Earth.

Camera-A : 25km/pixel @ apogee, 4.6km/pixel @ perigee
Camera-B : 50km/pixel @ apogee, 9.2km/pixel @ perigee

To simplify circuitry, SCOPE uses a TMP68301 chip that is built around a 68000 CPU. This chip has 3 channels of UART, timer/counter, address decoder, wait generator, interrupt controller and 16 bit parallel I/O port all integrated in a single chip.

The CPU clock is selectable between 16 Mhz or 8 Mhz which helps reduce power consumption.

A initial program loader is stored in an AMSAT space proven HM-6617 fused link ROM. Each SCOPE camera has two sets of fuse link ROMs for redundancy.

The CPU section also contains an RS-485 async port and CAN bus (Control Area Network) interface to be used to communicate with other onboard modules for program loading, commanding and transferring picture data.

The memory section has 4 MB of HM628512 SRAM (Static RAM) in total. Within this 4 MB, 1 MB has EDAC (Error Detection And Correction) capability utilizing a IDT39C60.

The A/D converter section has three identical A/D converters, one each for the red, green and blue CCD.

Each A/D converter has 8 bit resolution and with three of them 24 bit (16.7 million colors) will be reproduced.

Figure 11 - A picture from the second session of SCOPE testing, December 15, 2001

There is a variable gain amplifier (x1 - x8) between each CCD and A/D converter to adjust the signal level.

Output from the A/D converters is stored in 3 MB of non-EDAC memory by the CPU. The A/D converter section also contains driver circuits and temperature monitor circuits for the CCD block.

The power supply section receives +10.6V from the satellite power bus and supplies +5V, +15V and -9V to other SCOPE sections. LM2577 switching power supply IC's are configured as a flyback type power supply. To improve load regulation two similar power supplies are used, one supplies +5V only and the other supplies +15V and -9V. Power consumption is around 5W/camera.

A single bit switched by the IHU (AO-40 buss) turns on and off each camera.

SCOPE communicates with RUDAK via the CAN-bus or a RS-485 multi-drop serial link. SCOPE listens for boot load code as well as commands from the ground command station via RUDAK through the CAN-bus. Images captured by SCOPE are stored in RUDAK and then later forwarded down to ground stations.
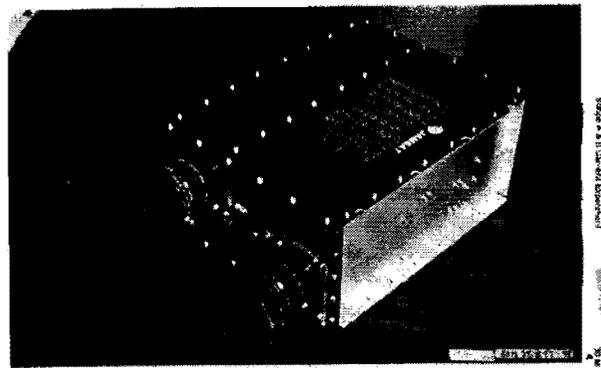
Figure 12 - The SCOPE camera module
An RS-485 multi-drop link serves as a backup to the CAN bus and links RUDAK and the two SCOPE cameras.

Software

Software that runs in the SCOPE CPU is first uploaded to the RUDAK file system. Once the SCOPE SCOS task is running a command is sent to that task which causes that binary file to be loaded into the camera CPU and executed. Further commands are then available to set the exposure, choose which camera to use, and take a picture. When a 'take picture' command is received by the SCOPE task it interacts with the SCOPE CPU to cause the image to be recorded and transferred to the RUDAK file system using a software defined file name partially based on time. Diagnostic messages are placed on the downlink to indicate progress and completion of the file move. Once the file is in the file system it is downloaded using the usual file transfer methods (the Pacsat Broadcast Protocol). Many pictures taken with both cameras can exist in the file system. Multiple versions of the SCOPE CPU code could be saved in the file system although this is not expected to be the normal operational mode. Once RUDAK is opened for general use any Amateur with a suitably equipped ground station can download these pictures.

Figure 13 - First picture taking by SCOPE wide angle camera, August 8, 2001

Operations

SCOPE was first exercised August 8, 2001. After a handful of pictures were taken at various exposures to characterize the operation of the cameras and lenses, the first published picture was taken using the wide angle camera. It showed a crescent earth floating in black space and was quite striking. Subsequently, on December 15, 2001, another set was taken with more of the earth illuminated. Both sets of pictures proved both cameras are working as expected.

Presently only the RUDAK command station is exercising SCOPE. However it is expected control will be transferred to the JAMSAT SCOPE team soon.

The first pictures were taken using the test and evaluation software and were time consuming to download. For each picture three full bit map images had to be downloaded, then byte swapped, merged, then compressed into .jpg format on the ground. Software to create color .jpg images in the camera CPU has been written and matching software to run in RUDAK is being created at the time of writing. This will make it possible to take a picture and download it in about 15 minutes or less as opposed to the 3 hours needed using the evaluation software.

The current images also suffer from blurring due to the spin of AO-40. The exposure time of the last pictures is .1 seconds so it should be possible to de-spin the raw images with post processing. If successful all the blurring at the edges should be eliminated. Of course when AO-40 moves into three axis stabilized mode this problem will go away.

Issues

The only difficulty encountered with SCOPE has been associated with moving large amounts of data across the CAN bus. CAN is not particularly efficient for moving large blocks of data. Software tricks to make it more efficient add complexity and software development time. These are however one time issues and will not effect ongoing operations.

It should be noted that successful implementation of the interface between RUDAK and SCOPE was facilitated by three face to face meetings of the respective software developers and the existence of two essentially identical SCOPE engineering units in their hands. Success would have been less likely and certainly more time consuming and costly without these units.

CEDEX is a re-housed version of the Cosmic-Ray Experiment (CRE) which already flies on the KITSAT-1 (KITSAT-OSCAR-23) and PoSAT-1 micro-satellites in low-Earth orbit. There are two sensors in the CEDEX experiment package.

Total Dose Experiment (TDE)

The TDE is based upon the AEA Technology (Harwell) design originally flown onboard UoSAT-3 (UoSAT-OSCAR-14) as part of the Cosmic-Ray Effects and Dosimetry (CREDO) payload, and is a direct derivative of the UoSAT-5 (UoSAT-OSCAR-17) variant. The purpose of the TDE is to measure the accumulated ionizing radiation dose inside the AO-40 spacecraft. This is done by a series of solid-state "RADFET" dosimeters (modified power MOSFETs) that have a thick (> 0.1 microns) gate-oxide to make them especially sensitive to ionizing radiation. Exposure to radiation causes the formation of trapped holes (positive charge) in the gate oxide, which in turn causes a gradual shift in the threshold voltage (Vth) with accumulated dose.

Cosmic Particle Experiment (CPE)

The purpose of the CPE is to characterize the AO-40 orbit radiation environment in terms of the observed particle Linear Energy Transfer (LET) spectrum inside the spacecraft. The data returned by the instrument are directly comparable to that obtained by similar instruments such as U.K.'s Cosmic-Ray Effects and Dosimetry (CREDO) and Cosmic-Ray Effects and Activation Monitor (CREAM) experiments which have flown on-board Concorde, the U.S. Space-Shuttle and UoSAT-3, and the Cosmic-Ray Experiment (CRE) flown on KITSAT-1 and PoSAT-1.

AO-40 represents a unique opportunity to characterize this high-eccentricity orbit. These data are also of great use in evaluating the radiation performance of the electronics used in the Phase-3D satellite.

Software

The CEDEX module runs from internal firmware that cannot be modified on orbit. In operation CEDEX attempts to connect to the CEDEX task running in the RUDAK module via the CAN bus and CAN server in RUDAK every few minutes. Once a session is established it sends packets containing CPE data to the CEDEX task every 10 minutes.

The RUDAK CEDEX task time-stamps the data and writes a record to a file in the file system. A new file is

created each UTC day with a unique file name keyed to the date. Those files are downloaded by command stations as visibility opportunities occur. The files are emailed to the PI who post processes them.

Results

Figure 14 - Clearly shows the form of the inner Van Allen (proton) belt.

CEDEX was first activated in December 2001. On December 15 the first files were collected and downloaded. Over the next 12 days data were collected that included about nine orbits of the satellite. Some of those data are plotted in figures 14 and 15.

The horizontal scale is in geocentric Earth-radii R_E (1=Earth's surface).

Because the magnetic field is not centered on the center of the Earth and the orbit precesses, there is a slight spread in count rates for each altitude.

The vertical axis plots the number of proton strikes in the detector over a 150 second integration period. The scale is logarithmic, - i.e. $5 = 100,000$ counts, etc.

The peak proton flux is clearly shown at ~1.7 R_E, as is an unexpected second peak at ~ 3 R_E. This second belt

is currently under investigation and may be related to recent solar flare activity – similar to the radiation belt created by the major flare of March 1991. A slight rise in galactic-cosmic ray flux is also discernable at high altitudes out to 10 R_E.

Additionally AO-40 has such a high apogee (about 10 earth radii), that it may prove possible to probe Earth's bow-shock region, if the apogee becomes coincident with the mid-day meridian. If collection of these data is accomplished it will represent data may be correlated with data from the CLUSTER mission.
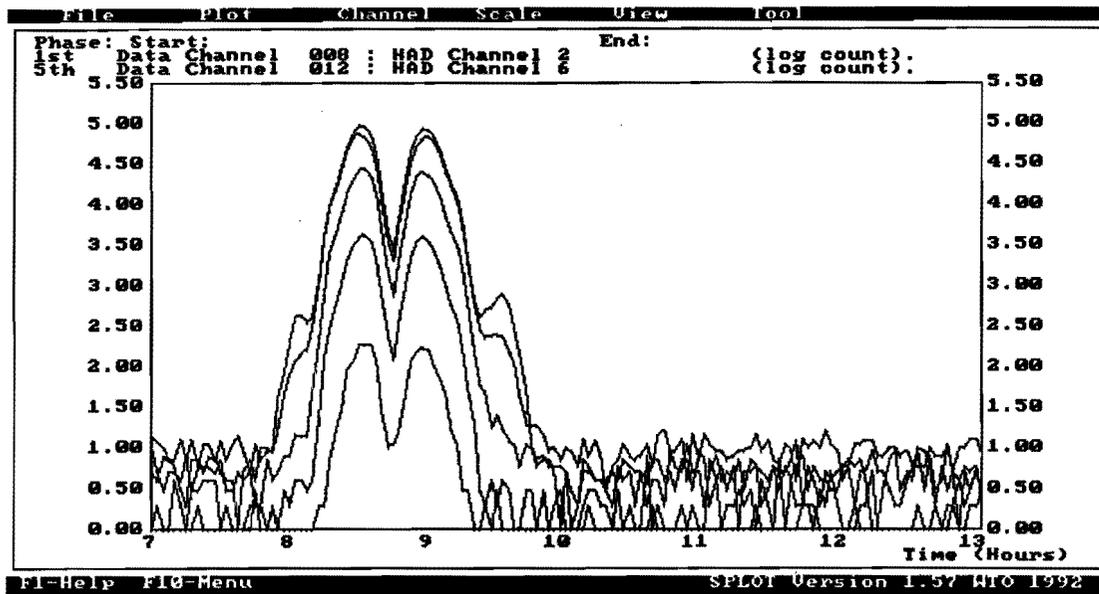
Figure 15 - Shows a "zoomed-in" view of the Van-Allen belt passage for the proton channels.

Channels 2 and 3 show the highest peaks (almost coincident in amplitude), with Channel 2 (and to some extent Channel 3) showing a curious second peak or "ring" around the main belt. This is very interesting indeed and needs further investigation. A double-peaked proton belt is not in the models!

Channels 4, 5 and 6 step down in particle flux more-or-less by a power law - as expected.

It took Phase-3D approximately 2 hours in total to traverse the belt (inward and outward bound).

Issues

CEDEX is the only experiment in AO-40 that when powered on autonomously wakes up and attempts to communicate with its managing task in RUDAK. This technique has proven quite successful in other satellites. Initial attempts to communicate with CEDEX indicated it was communicating with the CEDEX task but only time stamps were being logged to the file system. After the CEDEX experiment was powered off and back on proper communication was verified and data was logged. The reason for this initial difficulty is not clear at this point but is probably not related to the general idea of an experiment that autonomously attempts to communicate with a controlling task in a managing computer. Subsequent to that initial problem logging was successful until satellite power limitations required RUDAK and the experiments to be turned off for the sun-angle season. The next opportunity to work with CEDEX occurred in May and June, 2002. Through June 15, 2002, the symptom noted above again prevented logging data. Additionally the software in the RUDAK-B processor

where the CEDEX task was being run crashed several times. At this writing it is believed this is a software problem and it is being investigated.

Future operation of the CEDEX payload in AO-40 is anticipated and is a priority for the mission. The software to communicate with CEDEX and log its data is neither complex nor large, and consumes little processing time. CEDEX has proven to be quite successful and is a strong candidate to be flown on future AMSAT missions that include a main processor and file system software.

MONITOR

The ionosphere MONITOR experiment is designed for passive sounding the space above the ionosphere in the HF band between 0.5 and 30 MHz. It measures the received signal strength with a frequency sweep or a repeat measurement on a selected frequency. The principal investigator for MONITOR is Peter Bakki from the University of Hungary.

MONITOR searches for the signals of terrestrial HF broadcasting sites that have passed through the ionosphere. Broadcasting stations work with high radiated power which in parts of the world is considered environment pollution. The objective of MONITOR is to better understand how this effects the ionosphere.

A program objective is to make simultaneous measurements of signal strength from the earth and

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from the space. This will allow calculations of how much of the signal is reflected and how much passes through the ionosphere.

Hardware

The MONITOR processor is a 68HC11 with attached fuse link PROM. The receiver consists of two mixers. The first IF is 45 MHz, the second is 455 kHz, both have a bandwidth of 7.5 kHz. A linear IF amplifier stage measures the received signal strength in 80 dB dynamic range. AM demodulation of the signal is also possible. The system can sweep in the whole frequency range with step sizes of 5 kHz and 9 kHz or repeat the measurements on one selected frequency.

Communications

Monitor communicates with RUDAK via the CAN bus using the CAN-SU protocol. It responds to 5 commands which control its scanning, dwell, and strength measurement functions. It returns signal strength and frequency data to RUDAK for storage in the file system and eventual download to the ground.

Software

Firmware in MONITOR resides in PROM and cannot be uploaded from the ground. A MONITOR task runs under SCOS to allow control of MONITOR. That task allows all MONITOR commands and data to be passed through to the ground for testing and checkout and also provides a way to poll MONITOR for data and store it in the file system.

Status

Use of MONITOR requires the deployment of the HF antenna which is stored behind the deployable solar panels. Those panels will only be deployed when three axis stabilization has been executed. As of this writing MONITOR has not yet been turned on or tested.

Issues

Debugging communications with MONITOR via the CAN bus was time consuming for both the MONITOR developer and the author of the SCOS MONITOR task. However at launch MONITOR was fully functional.

Conclusions

The RUDAK module has proven to be a very flexible and reliable experiment controller. While initially time consuming to implement its ability to communicate using multiple hardware interfaces and protocols has been well proven over the past year. In fact only a small portion of its capabilities have been exercised to date. The difficulties experienced by the AO-40 satellite have had much more effect on its communication transponders than on RUDAK or the associated experiments. In fact all hardware tested so far has operated without any apparent ill effects.

The ability to load tasks that control experiments individually and to kill them and load others has proven to be quite flexible and efficient.

In the future we expect to exercise the DSP units to implement other data rates and modulation formats. We also expect to continue to gather data from the CEDEX experiment. The GPS receivers, which were not expected to survive the radiation environment this long, will continue to be operated as time allows. As soon as the SCOPE camera software modifications are completed we expect to take another series of pictures. Some orbit planning has indicated a few rather interesting photo opportunities occasionally arise such as the nearly full moon next to the limb of the earth.

When three axis stabilization is achieved the antennas will be pointed at the earth all the time. This will allow longer periods of excellent communication links and should result in more time to operate and communicate with RUDAK. This in turn will allow more use of the experiments. Because of the longer windows and lower path loss when the satellite is closer to earth it may also become possible to open one of the RUDAK units to general use by Amateurs world wide. At that point we will very likely allow downloading of SCOPE pictures by individuals at their own ground stations. Scheduling software will also allow pictures to be taken when the satellite is out of view of the command stations. This opens up the possibility of some very interesting pictures of the earth from about 1000 km taken with the wide angle camera. The others experiments will benefit as well from longer RUDAK operational times. Additionally the lower path losses may make use of the high speed links (153k6 kb) possible by stations with minimal equipment.

While it is unlikely RUDAK will be reproduced exactly for use in future satellites the interconnection techniques and software drivers have already been designed into new satellite projects. The lessons learned are already being applied. It is hoped the RUDAK design information, both hardware and software, will prove useful to others.

Contact and information sources

A great deal of information about RUDAK may be found at www.amsat.org. RUDAK data is at amsat.org/amsat/sats/ao40/rudak/

Information about the current status of AO-40, along with many pictures and some additional RUDAK data may be found on the AMSAT-DL web page, www.amsat-dl.org. The current status is at www.amsat-dl.org/journal/adlj-p3d.htm. Background data is at www.amsat.org/amsat/sats/phase3d.html. Most information is available in German, English and Spanish

The SCOPE Project pages are on the JAMSAT web site. A good place to start is www.jamsat.or.jp/scope/index_e.html. Information is also available in Japanese and German.

Acknowledgements

The authors wish to thank the other members of the RUDAK team for information and ideas, the JAMSAT team for the hardware information on SCOPE, Dr. Craig Underwood for the hardware information on CEDEX, and Peter Baki for the information on MONITOR.

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* P3A was lost due to the failure of the launcher, P3B became AO-10 and still operates when sun angles are favorable, P3C became AO-13 which has reentered after several years of service.

† qCF, from Quadron Service Corporation (www.quadron.com)

‡ AO-16, which finally crashed when a section of memory went bad.

§ Pun intended.

** Similar to UNIX pipes, though several tasks can exchange data through a single stream.

†† The file system task (MFILE) was originally written by Jeff Ward at Surrey Satellite Technology

Proposal for a FEC-Coded AO-40 Telemetry Link

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Abstract

This paper proposes a new transmission format for AO-40 telemetry that uses strong forward error correction (FEC) coding. During fading, this format performs *dramatically* better than the current uncoded format. Weak-signal performance without fading is also significantly improved. The proposed format can be implemented entirely in software and uploaded to the AO-40 IHU.

The coding methods presented here are not new. They are drawn from deep space telecommunication standards and from direct satellite broadcasting. These methods, and the open-source software modules I have written to implement them, are broadly applicable to other amateur satellite links. The time has come to make FEC a standard feature of every amateur digital satellite link.

Introduction

AO-40 uses the same 400bps BPSK Phase 3 telemetry format designed in the mid 1970s and first flown on Phase 3A in 1980. It was also used on AO-10 (1983) and AO-13 (1988).

This format was a significant improvement over the simple digital communication methods then in use by radio amateurs, such as CW and RTTY. But its only use of error control coding (ECC) is a simple cyclic redundancy check (CRC) that can only detect errors, not correct them.

The Phase 3 format did not use any of the powerful error correction codes that had just been introduced on deep space probes such as Pioneer and Voyager. Although these codes are easy to encode even on a IHU, they were just too complex to decode on the personal computers then available to hams. Dedicated hardware decoders weren't practical either.

The situation has completely changed. Today's personal computer is an extraordinarily powerful digital signal processing (DSP) and encoding/decoding engine. The Pentium/Athlon (PC) and Power PC G4 (Macintosh) CPUs even provide "vector" instructions specifically intended for high performance digital signal processing. Similar instructions were once found only in high-end supercomputers like Crays. Indeed, the average PC now significantly outperforms Cray's early models.

With these advances, it is now fully practical to realize the benefits of FEC on AO-40 and future spacecraft. The primary benefit would be a dramatic improvement in the reliability

of AO-40 telemetry when the antennas are off-pointed from earth and spin-induced fading is significant. Even under non-fading conditions, FEC coding would permit the acquisition of AO-40 telemetry with substantially smaller antennas than the uncoded format presently requires. The FEC format would also provide a substantial margin of safety during the commanding of spacecraft maneuvers.

Why Do We Need Coding?

DC power on a spacecraft is phenomenally expensive to generate, so it must be used efficiently. Downlink transmitters are usually the biggest loads, so great lengths have been taken to maximize power amplifier efficiency. (AMSAT has been a pioneer in this area with its development of HELAPS and similar technologies). A high altitude spacecraft like AO-40 carries high gain antennas to avoid spraying RF power uselessly into space. These in turn require accurate attitude determination and control.

Ground station antennas are often limited in size by practicality and local regulation. Amateurs use the quietest preamplifiers available, despite their high cost, but there are still natural noise sources that cannot be eliminated.

Amateurs have spent a lot of money and effort to maximize the amount of RF power their satellites beam to earth, and to maximize the signal-to-noise ratios of these signals as received at their stations. But two critical elements of the system remain unchanged: modulation and coding.

Binary phase shift keying (BPSK), as used by the AO-40 telemetry beacon, is one of the oldest and most widely used modulation schemes in space communications. Figure 1 shows the bit error rate of an ideal BPSK demodulator as a function of the "per-bit" signal-to-noise ratio.

The "per bit SNR" is more commonly known as E_b/N_o, the ratio of the received energy per data bit, E_b, to the noise spectral density, N_o. I will use that term in the rest of this paper.

This plot makes several important assumptions. First, the demodulator is "coherent"; it recovers the phase of the transmitted carrier from the incoming signal, and it does so perfectly. Second, the only channel impairment is "white" Gaussian noise, such as the thermal noise of a preamp. There is no fading. This is an important point we'll return to later.

According to the Nyquist Theorem, BPSK must occupy a bandwidth of at least 1 Hz for every bit per second of signaling rate. I.e., its "spectral efficiency" is 1 bit/sec/Hz. And according to the Shannon Channel Capacity Theorem, there exists a signalling scheme with a spectral efficiency of 1 bit/sec/Hz that can achieve error-free performance provided that the E_b/N_o is at least 0 dB. (No such scheme exists that requires an E_b/N_o of less than 0 dB.)

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Fig 1 – Uncoded Coherent BPSK
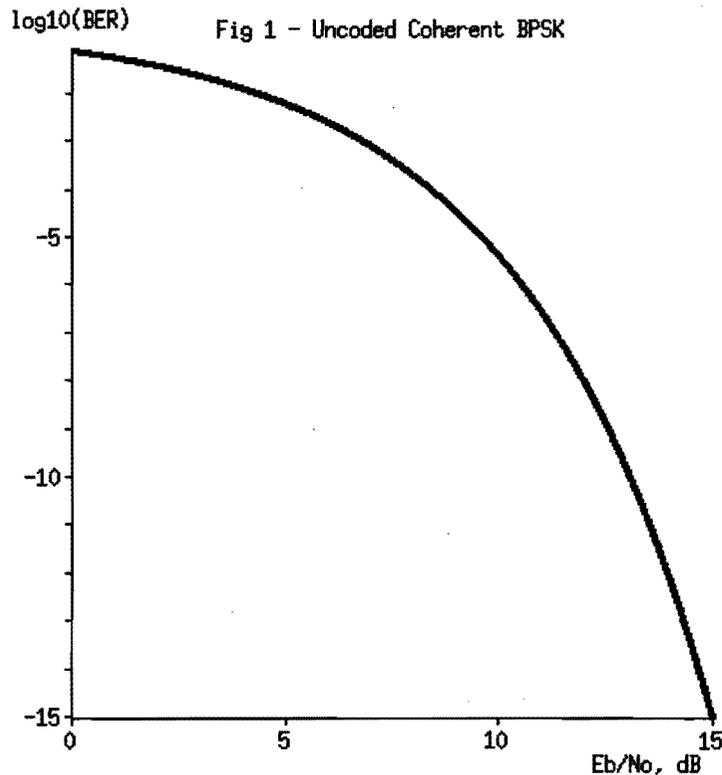
As you can see, achieving a good error rate with uncoded coherent BPSK, even with a perfect demodulator, needs about 10 dB more power than the Shannon limit requires. How can we make up at least some of the difference? With forward error correction coding. The power we can save with a given FEC scheme over uncoded BPSK is the coding gain.

Coding On Fading Channels

On a fading channel, the case for coding is even more dramatic. The Rayleigh fading model is commonly used, as it accurately models propagation over multiple, time-varying reflected paths. EME and HF skywave are well modeled by Rayleigh fading. The Ricean model generalizes the Rayleigh model by adding a direct free-space path to the indirect multipath components. Land mobile channels are often modeled as Ricean.

Except for satellites on HF, most amateur satellite link fading is caused entirely by satellite spin or tumbling combined with nonuniform antenna patterns. This is the case when AO-40's antenna is off-pointed from earth. The fading envelope repeats predictably on every rotation, and depending on spacecraft attitude, the envelope can include one or more deep nulls. Here is an amplitude plot of AO-40 S-band telemetry as received by W2GPS and WB4APR using the 12-meter dish at the US Naval Academy on January 18, 2001. The time span is 3.38 seconds, the spin period at that time. The receiver AGC could not be turned off, so the fading was even more severe than shown here:
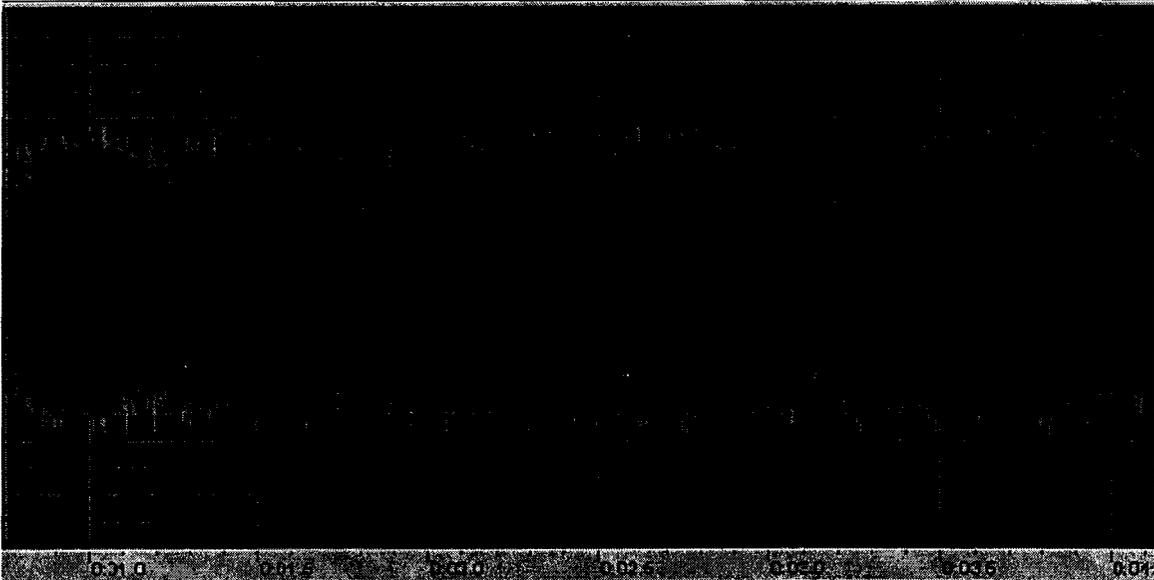
Without FEC, a telemetry frame is no stronger than its weakest bit. A short, deep fade that causes a single bit error is enough to destroy an entire frame even if the average Eb/No is high. Because a frame is about 11 seconds long and there can be multiple deep fades per satellite rotation when the antennas are not earth-pointing, every frame is almost guaranteed to have at least one bit error. With FEC, however, the bits corrupted in a fade can be regenerated from the others that are received. It doesn't matter how deep the fades are, as long as most of the frame gets through.

So the coding gain that FEC can achieve on a fading channel depends on the fade depth. FEC that can "ride through" say, a 30 dB fade, can provide a coding gain of 30 dB over and above that provided on a non-fading channel. We amateurs can no longer afford to ignore such dramatic gains!

The Concatenated Reed-Solomon/Convolutional Code

A complete review of all FEC codes would fill a large textbook, so I'll limit my discussion to the code I'm proposing for use on AO-40. This is the concatenated Reed-Solomon/Convolutional code first flown on Voyager 1 and 2 in 1977, and now widely used in very similar form by every major digital broadcast satellite.

A "concatenated" code is formed by combining two separate codes, in this case a Reed Solomon block code and a "short" convolutional code decoded with the Viterbi algorithm. (One sometimes hears the term "Viterbi code", but this is inaccurate. Viterbi's contribution was an efficient algorithm for decoding convolutional codes, which were already known at the time.)

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Here is a communications system that uses a concatenated code:
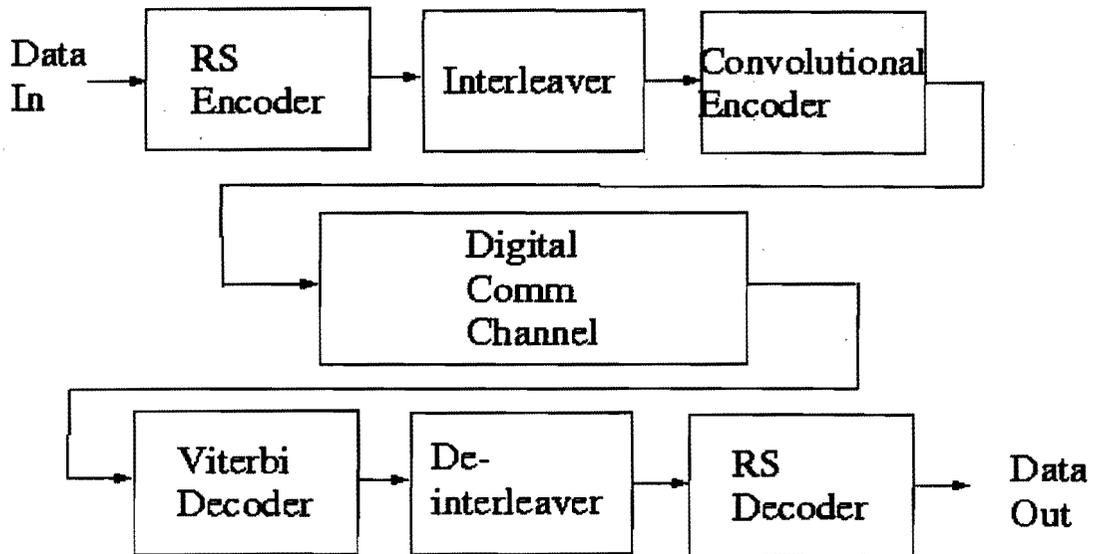
The user data is first encoded with a Reed-Solomon code. The Reed-Solomon data is interleaved (reordered) and encoded again, this time with a convolutional code. At the receiver, the convolutional code is decoded with a Viterbi decoder, the data is de interleaved and the Reed-Solomon code is decoded.

In this scheme the Reed-Solomon code is sometimes referred to as an "outer code", while the convolutional code is an "inner code". Why use two codes? And why the interleaver? To get the best of both kinds of codes.

Viterbi-decoded convolutional codes provide excellent coding gain on Gaussian channels with random channel bit errors, and they are readily adapted to soft decision decoding. If the demodulator can provide a "quality" indication with each incoming bit, the Viterbi algorithm yields an extra coding gain of about 2 dB over that from a demodulator with a simple slicer at its output. Typically 3- or 4-bit samples are used.

The Viterbi-decoded convolutional code first used on Voyager has become very widely used. It is a Consultative Committee for Space Data Systems (CCSDS) standard. Here is a block diagram of the encoder:
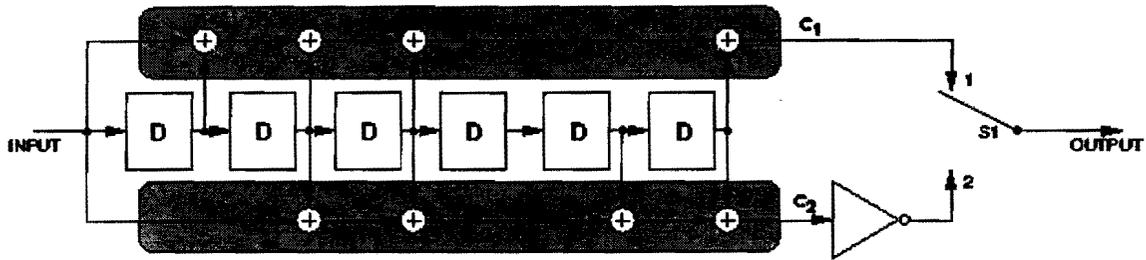
This particular code has a constraint length of 7 and a rate of 1/2. That is, there are taps at 7 points along the encoder shift register, and it generates two encoded channel symbols for each input data bit.

A description of the Viterbi algorithm is beyond the scope of this paper, but its performance on this code on a coherent BPSK channel with 3-bit soft decision symbols is shown here:
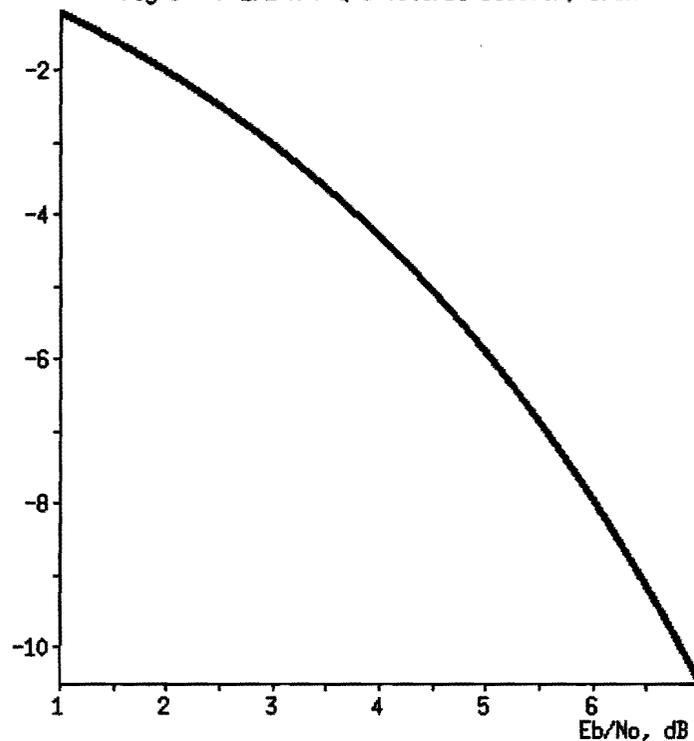
Note the improvement over uncoded BPSK. To achieve a bit error rate of 10^{-5}, the coded channel requires an Eb/No of about 4.5 dB. That's 5.1 dB less than uncoded BPSK. In other words, just by using this code you can cut your transmitter power by a factor of 3.2 and keep the same user data rate. Or you could increase your data rate by that same factor of 3.2 while keeping the same transmitter power, ground antenna, etc.

This does come at the cost of doubling the channel bandwidth, as the encoder generates two channel symbols for each data bit.

A Viterbi decoder still makes errors, and it cannot reliably tell you where they are. A telemetry system needs protection against these errors, so we need something else on top of the Viterbi-decoded convolutional coding.

One could just use a CRC, and some systems (e.g., IS-95 CDMA digital cellular) do just that. But if our data blocks are large enough, we can do better with a more powerful code.

Reed-Solomon (RS) codes are well known for their use in CDs and CD-ROMs. They are "block" codes like CRCs, only much more powerful. The RS code in my proposal is also a CCSDS standard, similar to Voyager's (255,223) RS code. Each code block contains 255 8-bit symbols. 223 symbols contain user data and 32 symbols contain parity computed according to the code specification.

A (255,223) RS code not only provides extremely reliable error detection, it can also correct up to (255-223)/2 = 16 symbol errors in each block. At least one bad bit in a symbol spoils the whole symbol; it doesn't matter if the other bits are also bad. This makes RS codes better suited to the correction of burst errors than random errors.

It turns out that Viterbi decoders always make their errors in bursts. This makes for an ideal marriage between a Reed-Solomon code and a Viterbi-decoded convolutional code. The Viterbi decoder does most of the work, and the RS decoder "mops up" most of the remaining errors. Any uncorrectable errors that remain are almost guaranteed to be detected.

When these two codes are combined, the BER curve is a nearly vertical cliff at an Eb/No of about 2.5-2.6 dB.

Applying the Concatenated Code to AO-40

Here is a block diagram of the complete frame encoder for AO-40. Besides the Reed-Solomon and convolutional encoders and the interleaver between them, several more components are included: a scrambler that ensures frequent symbol transitions regardless of the input data, and a second interleaver.

The current, uncoded Phase 3 telemetry frame has a data payload of 512 bytes. Early in the project, it was decided that a payload of only 256 bytes would be acceptable in the FEC format. This reduces the IHU RAM needed to build the encoded frame, and it keeps the frame from taking too long to transmit at the fixed rate of 400 bps.

256 data bytes

```
         ↓
┌──────────────────┐
│   (160,128)      │
│  Reed-Solomon    │
│   Encoder        │
└──────────────────┘
         │ 2560 bits
         ↓
┌──────────────────┐
│    2:1 byte      │
│   Interleaver    │
└──────────────────┘
         │
         ↓
┌──────────────────┐
│                  │
│    Scrambler     │
│                  │
└──────────────────┘
```

tail
6 bits   2560 bits

```
┌──────────────────┐
│  Convolutional   │
│  encoder         │
│  r=1/2 k=7       │
└──────────────────┘
```

65-bit   5132 bits   pad
sync   3 bits
vector

```
┌──────────────────┐
│   65x80 bit      │
│  block interleaver│
└──────────────────┘
         ↓
```

5200 bits
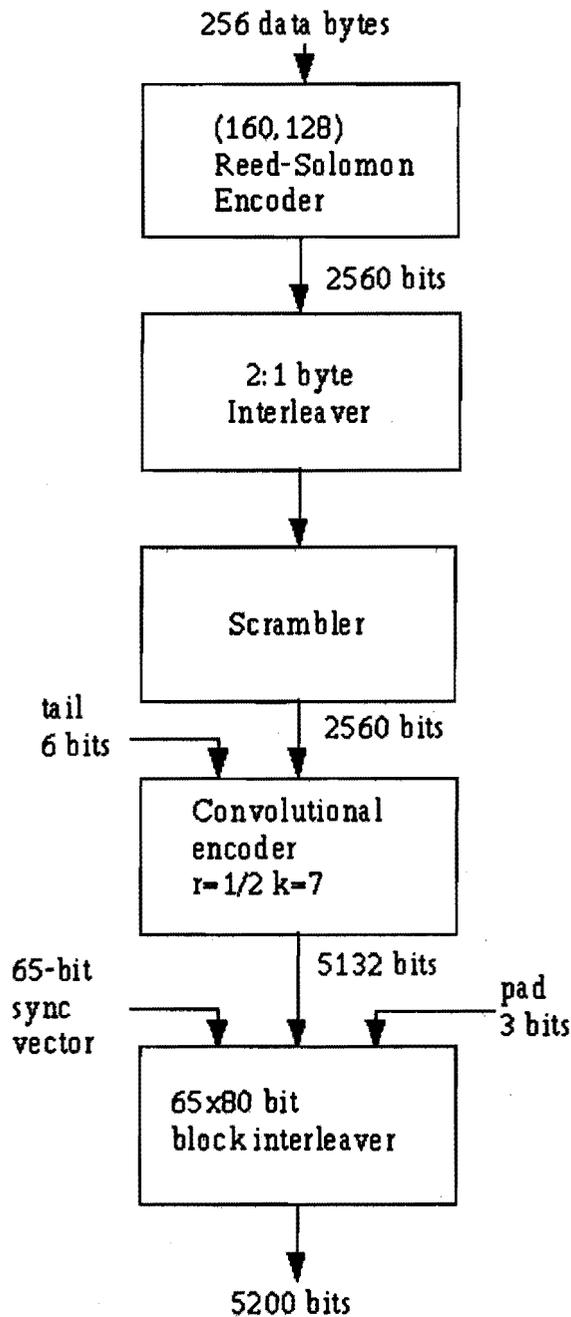
The 256 bytes of telemetry data are divided into two blocks of 128 bytes each. Each block is zero-padded at the start with 95 bytes of binary zeros to make 223 bytes of data for the Reed-Solomon encoder. This zero-padding is reinserted at the decoder; it is not sent over the air. This shortening process effectively turns the original (255,223) code into a (160,128) code. Each block still has 32 parity symbols and can still correct up to 16 symbol errors. Because fewer symbols are actually transmitted over the air, the percentage of symbols that can be in error is increased, strengthening the code at the expense of greater overhead.

The 320 bytes of RS-encoded data are interleaved, scrambled and fed to the k=7 r=1/2 convolutional encoder. A "tail" of six 0-bits is added to the end of the scrambled frame to return the convolutional encoder to the all-zeros state.

Because fade-resistance is a specific goal, a second layer of interleaving -- unique to the AO-40 format – was added after the convolutional encoder, just before the modulator. This is necessary because Viterbi decoders do not do well on fading channels. It was not needed on Voyager because that spacecraft is 3-axis stabilized and does not suffer from the kind of spin fading that affects AO-40.

For the same reason, the existing Phase 3 block sync vector scheme could not be used. A "distributed" sync vector, 65 bits long, is interleaved with the data so that a single fade at the wrong moment cannot kill the entire frame.

Each coded frame contains exactly 5200 encoded bits (binary channel symbols) and takes exactly 13 seconds to transmit at 400 bps. The user data payload is 256 bytes, or 2048 bits. The remaining 5200 - 2048 = 3152 channel symbols contain FEC overhead, a sync vector, and a few spare bits.

A more detailed description of the format, and the rationale for each design decision, is in my paper, Proposed Coded AO-40 Telemetry Format, published on my web page at http://www.ka9q.net/papers/ao40tlm.html.

Demodulators For Fading Channels

The coherent BPSK demodulators commonly used with Phase 3 telemetry often have trouble maintaining carrier lock on a fading signal. Not only are the amplitude variations a problem for the carrier-tracking loop, but there can be a significant Doppler component due to antenna motion, especially at S-band. And there can be sudden phase jumps associated with specular reflections off spacecraft components. Strong FEC won't help us if the demodulator can't track the signal.

The answer is to use differentially coherent demodulation (DBPSK). A coherent detector extracts its carrier phase reference from a relatively wide sliding window of received symbols, but this window is a big target for a channel phase disturbance. DBPSK only uses the phase of the symbol immediately before the one we're demodulating, so a short disturbance only affects a few symbols.

For DBPSK to work, we must specially encode the data at the transmitter. I.e., we want to encode a 1-bit not as a particular carrier phase, but as a change of phase from one symbol to the next. Similarly, a 0-bit is encoded as no phase change. That allows us to recover the data by directly comparing pairs of received symbols.

Fortunately, AO-40 already does this. The IHU includes a hardware differential encoder and a Manchester (bi-phase) encoder. If a 1-bit is to be sent, the 400 Hz beacon clock is inverted in phase from its previous setting; if a 0-bit is to be sent, the beacon clock phase

is left unchanged. Bits thus encoded are then fed to the BPSK beacon modulator and to the transmitter.

DBPSK can be demodulated in software as follows. We take the digitized audio signal from the receiver and feed it to a complex (I&Q) mixer and low-pass filter. The mixer "local oscillator" is set close to the incoming carrier frequency. This produces a complex baseband signal with a carrier frequency close to zero hertz. (This is commonly known as a "zero IF" conversion.)

Because the LO is not locked to the carrier, the zero-IF signal vector will slowly rotate in phase. The closer the LO is to the carrier frequency, the slower the vector rotation. At the same time, the vector will flip 180 degrees and return according to the modulation.
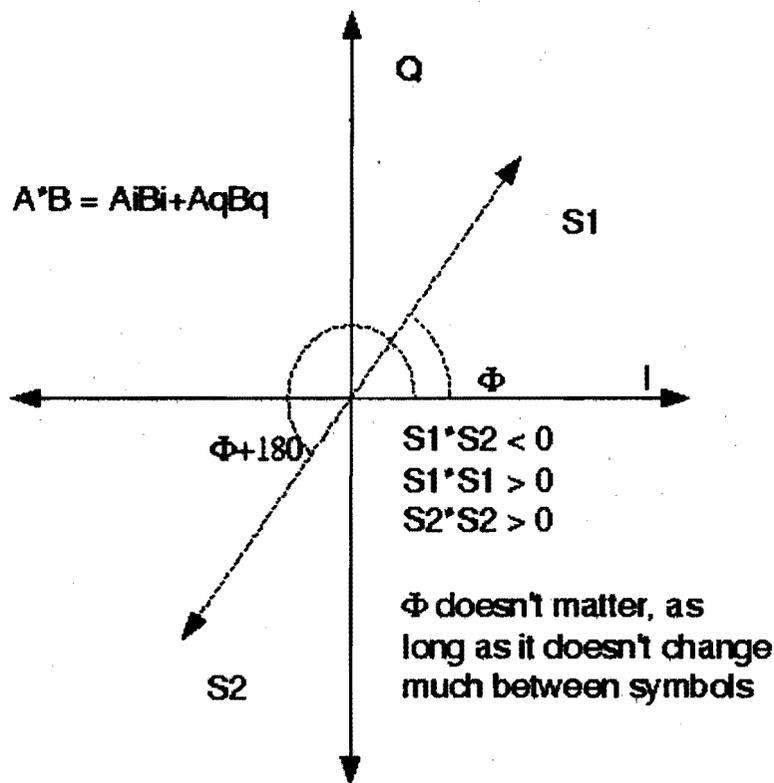
To extract the modulation, we compute the vector dot product of the complex baseband signal samples for the previous and current channel symbols. If there has been no change in phase between the two symbols, the dot product will be a positive number. If the phase has changed, the dot product will be negative. The magnitude of the dot product depends on the vector magnitude of both symbols; if the symbols are weak, the dot product will be small. We just flip the sign on each dot product, and we have our soft-decision values for our Viterbi decoder!

There's a little more to the problem. We have to know where each symbol starts and ends, and we also need to know the approximate incoming carrier frequency so that the zero IF signal vector won't drift too much between each pair of symbols (not counting the modulation, of course).

Given the power of the modern PC, simple brute force works well here. I start by simply trying all possible combinations of carrier frequency and symbol timing, looking for maximum demodulator output. But I need not do this on every frame. Carrier frequency and subcarrier phase usually don't change much from one telemetry frame to the next, so I can simply use the values acquired for one frame as initial guesses for the next. If the guess is right, the frame decodes. If not, I can drop back and retry the frame with the brute-force search.

All this is still a lot easier to implement than coherent BPSK (CBPSK) demodulation with a Costas or squaring loop. And while DBPSK works well on channels with rapid carrier phase disturbances, CBPSK often fails completely.

But DBPSK has its price. On a non-fading channel, CBPSK outperforms DBPSK. A coherent detector produces a carrier phase reference from the energy of many channel symbols, while the DBPSK demodulator can use only the energy of one symbol as a reference.

At high Es/No ratios, such as those required for uncoded PSK, the advantage of CBPSK over DPSK is only a small fraction of a dB. (Es/No is the signal-to-noise ratio seen by the demodulator rather than the FEC decoder. In an uncoded system, a channel symbol and a data bit are the same thing, so Es/No = Eb/No. We've seen that this has to be about +10 dB for uncoded BPSK). This raises the question of why so many Phase 3 BPSK demodulators use coherent detection despite the increased complexity and difficulty in use.

But in a FEC-coded system, the Es/No is the Eb/No times the code rate: about 0.4, or -4 dB in the present scheme). Thanks to the FEC coding gain, we can operate at a much lower Eb/No of about 2.6 dB, and the Es/No is another 4 dB below that, or about -1.4 dB. That's low enough for the DBPSK penalty to become significant.

Test Results

I have tested my prototype demodulator on simulated channels with Gaussian (thermal) noise and with and without fading. Both NRZI and Manchester symbol filtering were tested, although only Manchester is compatible with the AO-40 IHU. (More on this later).

NRZI encoding, Gaussian noise, no fading

Virtually 100% frame copy is achieved at Eb/No >= 6 dB. At Eb/No <= 5 dB, no frames are decoded at all. This sharp threshold is consistent with my use of the concatenated

code, only it occurs 3.4 dB higher because I use DBPSK demodulation rather than coherent BPSK. However, I'm still 4 dB better than uncoded BPSK.

NRZI encoding, Gaussian noise, sinusoidal fading

In this test, the signal is first multiplied by a 3.3 Hz sinusoidal envelope to simulate spin modulation. The fading envelope goes through two nulls and two carrier phase reversals per cycle. Noise is then added to make a specified average Eb/No, i.e., the signal peaks are higher than in the non-fading case.

In this case, 100% copy is achieved at Eb/No >= 8 dB, but only about 10% of the frames are decoded at Eb/No = 7 dB. In this particular situation, the addition of fading results in about a 2 dB impairment.

Biphase encoding, gaussian noise, no fading

This test uses a transmit filter with an impulse response derived from analysis of the hardware filter in the AO-40 beacon transmitter. The demodulator uses an identical matched filter.

Solid copy is achieved at Eb/No >= 7 dB, and 50% copy at Eb/No = 6 dB. This is about 1 dB worse than with NRZI. This is due to inter-symbol interference in the transmit filter that is unequalized in the receiver. A receive equalizer should remove most of this penalty, but some may remain.

Biphase encoding, gaussian noise, sinusoidal fading

Solid copy at Eb/No >= 9 dB, ~50% at 8 dB, and no copy below 8 dB. This is consistent with the 2 dB penalty seen in the fading NRZI case, and with the 1 dB penalty due to the unequalized biphase receive filter.

Discussion

These tests clearly demonstrate the benefits of FEC and DBPSK demodulation under non-fading and, especially, fading channel conditions. Although at least 4 dB of margin is provided on a non-fading channel, the really dramatic improvement is on the fading channel. Because the simulated fading envelope passes through zero amplitude (minus infinity dB), copying this signal without FEC would be totally futile even when the average Eb/No is extremely high. Yet with the FEC format, fading signals that are barely audible to the ear at fade peaks can be reliably decoded.

The FEC format's fade tolerance depends on fades being brief relative to the 13 sec frame time. Tests do show worse performance on very long fade periods, as expected. This could be improved with a longer interleaver, but only at the expense of increasing the delay between the generation of a frame by the IHU and its decoding on the ground. So

13 seconds was chosen as an initial compromise. If experience shows that a longer interleaver would be desirable, the format can be changed.

On a fading channel, we have no choice but to use differentially coherent (DBPSK) demodulation. But I could improve the performance of my demodulator under non-fading conditions by adding a CBPSK demodulator. DBPSK could be tried first, and it will succeed if the signal is strong enough. If not, the CBPSK demodulator could then be tried automatically.

Another possible enhancement is suggested by the technique developed by Paul Willmott, VP9MU, to merge AO-40 telemetry fragments from multiple stations. This recovers data that might not be available from any one station. This approach is even more powerful when FEC coding is in use, and it is routinely performed on signals from the Galileo spacecraft orbiting Jupiter. An array of antennas and receivers is pointed at the spacecraft, and the separate signals are synchronized and combined before demodulation and decoding.

Prototype Software

My software prototype implementation of an encoder, channel simulator and demodulator/decoder is available on my web site, http://www.ka9q.net, under the terms of the GNU General Public License.

The prototype package uses a set of general-purpose DSP and FEC libraries that can easily be reused in other projects:

DSP

This library implements a set of basic digital signal processing (DSP) functions, such as the "dot product" operation key to convolution and digital filtering. The implementation uses the MMX, SSE and SSE2 instruction sets, where available, and a portable C version on all other CPUs.

Reed-Solomon

This library implements a family of Reed-Solomon encoders and decoders, including the CCSDS standard codecs used in the AO-40 format.

Viterbi Decoder

This library implements Viterbi decoders for two popular convolutional codes, including the k=7 r=1/2 code used in the AO-40 format. MMX, SSE, SSE2 and portable C versions are all provided.

Demodulation and Decoding Speed

Once acquisition occurs, real-time telemetry demodulation and decoding takes less than one percent of a 1 GHz Pentium III CPU running Linux. Acquisition takes more because of the brute-force search for carrier frequency, symbol timing and clock rate. To eliminate unnecessary CPU loading, the demodulator could be automatically disabled whenever when the spacecraft is below the horizon.

Conclusion

Powerful forward error correction techniques are ripe for amateur satellite use, especially on downlinks and on uplinks contaminated by radar interference. An encoder for the concatenated Reed-Solomon/convolutional code proposed here requires minimal resources, and can be easily implemented in the AO-40 IHU. On future satellites, an encoder could be easily integrated into the housekeeping software, or perhaps in a small dedicated microcontroller. When spacecraft CPU cycles are available, the cost of FEC is essentially nothing, but the benefits are enormous.

Credits

I'd like to thank the following people for their ideas, suggestions, data and other significant contributions to this project: Rick Hambly, W2GPS; Bob Brunega WB4APR; Jan King, W3GEY; Tom Clark, W3IWI; Peter Guelzow, DB2OS; James Miller, G3RUH; Stacey Mills, W4SM; Bob McGwier, N4HY; and Ron Parise, W3SIR.

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HOW KIDS CAN TALK TO SPACE PEOPLE
(Who are aboard the International Space Station)

by Gene Chapline, K5YFL

We are the space people. When the International Space Station was occupied permanently in October, 2000, we became a species that will probably forever and always have some of its members away from the home planet. That fact, its implications and consequences, must now be part of our children's curriculum. We are no longer sending our kids out into the world, but into the universe.

There is an exciting way to open a window into space for students in a classroom. It's done by letting children talk directly to crewmembers on board the International Space Station by means of amateur radio. It's being done four to six times a month, and there's no lack of attention from the students. Immediately after one such contact an elementary school principal in Texas beamed, and fighting a big frog in her throat, said, "I think maybe we started some dreams this morning!" When students at a school in Mississippi completed a contact, their teacher exclaimed, "These students are going to have a very slow time of landing back on Planet Earth, and the parents are still on Cloud Nine." It's no secret that kids eagerly jump into learning everything about what excites them. As NASA's Director Sean O'Keefe (a father of three) said in March of 2002, "...if it excites kids, that is what is going to get to the kids."

The radio contacts are made through a program called Amateur Radio on the International Space Station (ARISS). ARISS is an international project, with U.S. participation by NASA, the American Radio Relay League (ARRL) and Amateur Satellite Corporation, NA (AMSAT), a non-profit corporation. In 1996 NASA wanted a single focus for the development and operation of amateur radio on the International Space Station, and ARISS was the solution. In 1997 amateur radio organizations from eight of the 16 nations participating in the Space Station signed a memorandum of understanding chartering ARISS. The international partners then divided up chores and duties in preparation for the occupation of the Space Station in the fall of 2000. The first ARISS radio contact with a school occurred in late November, 2000. Since then ARISS contacts have been made with other schools, museums and special events such as the 2001 National Boy Scout Jamboree.

So how does your group of kids get in line to talk to space people? This article tells you how to put together a successful ARISS contact, taking you through a four-step process: application; preparation; the contact; and, the morning after.

APPLICATION:

Yes, you start with paperwork. You have to apply. Get on the internet, go to http://www.arrl.org/ARISS/ariss-ap.html, and print out the application form.

Now fill it out. Completely. The volunteer mentors of the ARISS Operations team need to know all the telephone numbers, e-mail addresses and physical addresses that are requested on the form. They will have to pry them out of you later if you don't provide them at first. They must be able to communicate with you, especially during the last few days and hours preceding an ARISS contact.

When you get through the getting-to-know-you part of the application, you will then encounter questions asking you about radio equipment, coordinates and elevation. You must now ask yourself, "Do I want to have a telebridge contact or a direct contact?"

Telebridge contact:

A telebridge contact is easy. It's done by telephone. The actual radio contact is through a ham station somewhere else in the world, and the audio is then carried to your location by a telephone connection provided by Worldcom, Inc., which sets up the connection and picks up the tab. A moderator will talk to you and your kids over a speakerphone before and after the actual contact. When radio contact is made with the Space Station, you will hear the crewmember over the speakerphone, and the students will ask questions over the speakerphone. It's simple. Your only technical responsibility is to provide a speakerphone of good quality, the kind used for teleconferences. Your local telephone company should be able to give you some guidance.

Telebridge contacts can be scheduled at times convenient for you and your students, since your contact with the Space Station is not dependent upon the spacecraft passing over your location.

If you opt for a telebridge contact, skip the questions concerning equipment, antennas, coordinates and elevation, and go to the part of the application asking about your educational proposal.

Direct contact:

A direct contact is made with amateur radio equipment set up at your location. If you are not a ham, you will have to seek out the help of hams in your area. The hams should have experience at satellite communication and should have the equipment necessary to accomplish a successful contact of ten minutes with the Space Station. You should be prepared to have wires, cables and antennas underfoot and overhead for a day or two. Everyone should be prepared to be flexible, diplomatic, and able to derive fun from the special circumstances and

difficulties. Direct contacts can be very exciting because everyone gets to see the operation of the radio equipment.

The application asks you to specify times and holidays during which it will be impossible or extremely inconvenient for you to gather your kids together. Be truthful in your response, or you may find that when your turn for a direct contact comes up, you are assigned a pass that you would rather not have. Time and tide and orbital mechanics wait for no one. When it's your turn, and the Space Station is due to pass over your location, it's step up, or go to the end of the line. The ARISS operations team tries to schedule contacts at reasonable hours, but unless you specify otherwise in the application, you may find yourself getting up before the chickens. If you should be assigned a dawn contact, just take some coffee, doughnuts and breakfast tacos for everyone at the contact site. It's all part of the fun.

If you opt for a direct contact, continue filling out the application questions concerning radio equipment, antennas, coordinates and elevation. A local ham who will be helping with the contact should fill out this section of the application. Make sure the answers are truthful, or at least will be true at the time of the contact.

Educational proposal:

At the end of the application will be a request for you to set forth your educational proposal. It will be necessary for you to write one. Don't skip over the section. Talking to the space people is not just for the fun of it; it fulfills specific educational purposes and goals of NASA and the ARISS project. The educational proposal is extremely important. It should include specific answers to these specific questions:
1. How will you integrate the contact into the curriculum of your school or the activities of a special event sponsored by a museum or youth organization.
2. How will you involve as many grade levels as you can through essay contests, poster drawing, letter writing and similar activities.
3. How will you get as much media coverage as possible? (The first two questions are more important than this third one.

Upon completion of the application, send it electronically or by mail to the ARRL at one of the appropriate addresses given on the form.

PREPARATION:

In the fullness of time (some applicants waited five years, but the waiting time is now much, much shorter), perhaps 10 to 18 months, you will be notified by a mentor from the ARISS Operations team that your organization's turn is approaching. The mentor will review the application with you to make sure that it is accurate and current, and will answer any questions you may have.

Equipment:

If you opted for a direct contact, you and the mentor will now begin to make sure that the equipment and antennas specified on the application form by the experienced amateur radio operator really exist in the form of an efficient station equipped with a primary station and a backup station.

The primary station should have a two-meter transceiver with frequency memory capable of operating in non-standard split-frequency mode. The transceiver should feed an amplifier putting out 80 to 150 watts of power into a 10 to 14-element circularly polarized yagi mounted on an az-el rotator controlled by a computer with an accurate satellite tracking program and tracking interface. A receive preamp would be helpful.

The backup station should have an uninterruptable power supply or a battery as its power source for a separate two-meter transceiver and amplifier with the same specifications as the ones for the primary station. The antenna may be an eggbeater-style vertical, a discone antenna, or a quarter-wave whip. Do not expect these backup antennas to do as good a job as a 14-element circularly polarized yagi antenna. Do not use a collinear or other vertical gain antenna, or you will have poor contact with the Space Station when it is overhead. The backup station is designed for operation if your building's AC power is lost. If you have a deep-cycle marine battery and a 600-watt inverter to power a computer and az-el rotator, you can go back to having a good antenna for the backup station.

Place your antennas in the clear, free of obscuration of the predicted path of the spacecraft. If trees or buildings will block the field of a ground-placed antenna, place the antenna on the roof of the building of the contact site. If the building has a flat roof, it easy to place a ten-foot section of tower on a base plate anchored by six cinder blocks. Place the az-el rotator and antenna on top of the ten-foot tower. Run the coax down to the room below. It's that easy. One radio crew for an ARISS contact tried to get by with less than what they promised on their application. They used a four-element vertically-polarized yagi mounted four feet off the ground, and pointed through trees on both horizons. They made contact, but not for ten minutes.

Some hams will tell you that the specifications prescribed by this article are overkill. It's not overkill when you have ten eager youngsters ready to talk to an astronaut in space for the full duration of a ten-minute pass over their school. Some hams will tell you that they've made contact with the Mir space station or the International Space Station using just a quarter-wave whip antenna. They have, but not for ten minutes. They may tell you that they've worked through satellites using just a handheld transceiver and a handheld yagi antenna. They

have, but not for ten minutes. They may have tasted success, but not for ten minutes. A successful ARISS contact lasts ten minutes, not four, nor five, nor six.

Choosing students:

This part of the preparation is often the most difficult for a teacher or events administrator. Somehow only a few students must be selected to ask questions of the crew. It is beyond the scope of this article to suggest selection methods to those who work with such students daily. However, a suggestion on the number of students to be selected is in order. The magic formula seems to be ten students and twenty questions. A Space Station pass lasts ten minutes, enough time for about twenty questions to be asked and answered. If ten students ask one question each, going to the end of the queue after each question, each student will get at least one shot at asking a question. If more than ten students are in a queue, there is always a chance that someone will not get to ask a question. That is always disheartening for any kid, and is an absolute disaster for the little ones. No one wants to wipe tears from the face of an eight-year-old, and no one wants to see such a picture in the local newspaper.

Uplink information:

Your mentor will ask that you provide some information that will be sent to the Space Station about 10 days before the contact. This "uplink information" will consist of two paragraphs of information about the school, the names of the students, and the questions that each will ask. The first paragraph about the school may consist of the school's history, it successes, or anything else that falls with the bragging rights category. The second paragraph should be a summary of the educational proposal, describing how the contact has been integrated into the curriculum or special activity. Then list the names of the students and their questions in the same order as they will speak to the astronaut, e.g.:
1. Emily Gofirst: What is the ...?
2. Steven Secondly: How is the ...?
Proceed until you run out of names and questions. If you have ten students who have two questions each, run through their names twice. For instance, in the example above, Emily would be Numbers 1 and 11; Steven would be Numbers 2 and 12.

This uplink information is very helpful to the astronaut who will be answering questions. It allows time to think and to prepare concise answers.

Systems checks:

Successful ARISS contacts are the result of checking, rechecking, and checking again. During the day before the scheduled contact, do an end-to-end check of the primary and backup stations several times. Have someone with a handheld rig programmed with the Space Station's transmit and receive

frequencies act as a proxy Space Station in rehearsal contacts. One ARISS contact failed because the ground station had its microphone gain control set to zero. An end-to-end check would have revealed the oversight.

Update your computer's keplerian elements a few hours before the contact using a source suggested by your mentor.

Use WWV as a source to correct your computer's clock and everyone's watches.

Make sure that you have a key to the contact site.

Make sure your mentor has the correct telephone number for the contact site.

Write a list of things to remember.

Have someone with the same list help you remember.

Have the students rehearse their questions. Run through several mock-up contacts using a chalkboard eraser as a microphone for the students to speak into. Instruct them to speak loudly, slowly and clearly.

The 24-hour notice:

Your mentor will insist that you send an e-mail notice or a fax confirmation that you are ready 24 hours before the scheduled contact. That little notice will keep the entire process in motion. Little things mean a lot. If you do not send the notice, the contact may be cancelled so that the crew may do other things. The mentor will send you a form to use in composing the notice.

THE CONTACT:

This part of the process is the easiest part for you. If all goes well and as rehearsed, you will be doing nothing. The contact is between the astronaut and the kids. It's for them only, not you. The adults on the ground stay away from the microphone and keep their lips zipped; no showboating or speechmaking. The ten precious minutes of the contact are not for you to speak, but to observe and enjoy.

When the signals from the Space Station fade over the horizon, the ten minutes will have passed away, and the contact will be over. The room will be silent for a moment before someone will yell or clap. You may then begin speaking if you wish.

Good luck. A teacher in South Carolina said that she knew an attempt at academic instruction would be a lost cause immediately after her junior high students made a contact. She instead let them view the movie "October Sky," the movie version of Homer Hickham's book, "Rocket Boys." That strategy was in keeping with her goal of keeping her kids' enthusiasm and excitement for learning alive.

THE MORNING AFTER:

The adventure ends as it began, with paperwork. You must file a final report. It may be filled out online at a NASA website which your mentor will refer you to. The report becomes part of a file which justifies the existence of the ARISS project and NASA's support of its educational goals. Your report helps to justify continued funding and help for the ARISS project. Your report helps to keep that window to space open for students.

CONCLUSION:

The mechanical success of an ARISS contact is measured by ten minutes. The effective success of an ARISS contact is measured in units still to be determined. How wide have imaginations been broadened? How deep has curiosity gone? How many more questions are now being silently asked? What wondrous answers will come?

Making a Case for Amateur Spectrum through Research, Education and Industry Cooperation

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ABSTRACT

Radio spectrum is allocated for the benefit of the public. The public demands and enjoys the use of VHF and above for new consumer devices, cellphones, and specialized commercial satellite services. Increased demands for spectrum by commercial services puts pressure on the FCC allocation for amateur radio use. Concerns for economic efficiency and social utility do not, on the surface, strongly support amateur allocations.

In this paper, we describe the problem we must face in justifying our use of precious spectrum. We note three useful approaches to protection of our spectrum: social support, legislative action, and industry support. Though each has merit, we focus on the industry support approach. We find this approach has the strongest long term possibilities to foster and to demonstrate the social benefits of amateur radio use of the spectrum. It has the secondary benefit of placing educated amateurs into professional relationships with the very industries that seek spectrum themselves.

The power and pitfalls of this approach are examined in the context of a real educational project that relies on amateur radio for its viability: CUBESAT. The CubeSat project links many educational institutions in an effort where students design, fabricate and launch small satellites into space. The effort is organized to be relatively inexpensive and to provide a standard platform for experiments in miniature space technologies. Amateur radio is

the ideal communications link for such satellites, but more importantly, such satellite projects are ideally suited to showcase the specific social benefits provided by amateur radio!

This paper will suggest an analysis of the costs and benefits of an approach to protection of our spectrum. There are strong possibilities for increased understanding of the benefits of amateur radio to society and in particular, to the industries who might desire more spectrum themselves. A call for a firm code of ethics is necessary for all amateurs who want to mentor students involved in this effort.

1. INTRODUCTION

The authors are each college instructors, long time hams, involved in the early stages of the CubeSat project[1]. We've been asked to help incorporate amateur radio into these small satellites that carry simple student experiments supported by industry.

The Ethical Dilemma

What about the ethical use of amateur radio? CubeSat is *not* about repeaters in space, nor is it primarily a radio oriented experiment. In fact, some of the data produced by flying industrial experiments may result in new technologies

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[1] For a more thorough overview of CubeSat and the Cal Poly / Cuesta College efforts, go to: www.polysat.org and to www.cubesat.org

useful to the industry supporters. Is this proper? We had to struggle with this question.

The Opportunity

In our thinking about justifications for using amateur radio to support such a project, we came upon the deceptively simple conclusion: we're doing nothing new! In fact, not only is the use of amateur radio proper[2] in this case, it is actually *necessary*. It can be the basis of a very strong social justification for our use of spectrum at UHF and above, and we generate technically competent amateurs to boot! By the same token, *we can demonstrate the value of amateur radio as an educational tool* to the very industries who covet amateur spectrum allocations. This may be the strongest ally we can hope for in our quest for spectrum preservation.

The Experience Report

In our experience with the CubeSat project, we've accidentally discovered the many virtues of amateur radio as an educational medium for engineering students, and of industry cooperation for amateur radio itself. The report is a rough account of the challenges we've faced and details the interfaces to amateur radio and industry.

2. WHAT IS THE PROBLEM?

The central problem for this work is amateur radio spectrum preservation, especially at UHF and above, where industry pressure on our allocation is greatest.

There is another, maybe more important question to be answered: who shall we convince that amateur radio allocations deserve protections? How shall we make that argument?

The Context to the Problem

The fact is that we amateurs have no constitutional right to our spectrum. Spectrum is allocated by the United States government on the basis of the social value of the activities carried on there. The higher the social value of the activity, the stronger the claim to limited

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[2] As long as proper ethical guidelines are coupled with knowledge of FCC and IARU rules and regulations. This is discussed later in the paper.

spectrum. If an activity is seen to be of low social value, spectrum may be reallocated to some other activity with greater value.

Cell phones, wireless networks, small consumer wireless devices are proliferating at a fast pace. The most desirable spectrum is at UHF and above, and competition for the amateur allocations is becoming more intense than ever before. The competition is legitimate and offers compelling reasons for its existence and increased spectrum allocation: public convenience and safety. An enormous economy is generated by these legitimate public needs.

In the past, amateur radio had clearly defined social benefits that justified social support for spectrum allocation. Amateur radio provided much needed CW operators for military operations and a cadre of experienced technicians for the military and for industry. Amateur radio operators pioneered repeater technologies that provided the very basis for much of the consumer devices that now compete with us for spectrum.

Where are the justifications for the amateur allocation today? CW is no longer socially valued. Technicians are not being produced by amateur radio in as great numbers as in the past. The social value of HF communications has all but disappeared. Much of the common amateur technology is not cutting edge at all, but closer to consumer electronics.

So, why should the amateur radio allocation at UHF and above be socially valued? We amateurs need to make arguments about why our allocation continues to return benefits to society.

3. SOLUTION APPROACHES

Since our purpose is to protect and preserve amateur spectrum at UHF and above, we outline some major approaches to a solution. We find three general approaches possible:

o   a pure legislative approach;
o   a social support approach; and,
o   an industry support approach.

These are not meant to be exhaustive, but to present the main ideas for examination and analysis.

The Pure Legislative Approach

One way to preserve our amateur spectrum allocation is to lobby congress and to obtain political support in the government. Good examples of this approach abound with ARRL actions on our behalf over the years.[3]

Though we believe this approach has merit, it is limited in its power. We see the size of the amateur's political base and the resources of the ARRL as limiting factors when competing with huge, wealthy industries that cater to the needs of the vast majority of the American public. In a capitalistic environment, we can make progress but have little power to fight any big fight.

The Social Support Approach

Another way to generate support is to convince the general population of the value of the amateur allocation. This often takes the form of publication of the successes of amateurs in public service activities. This approach is widely practiced by the ARRL and many local clubs. Good examples are given each month in QST's "Media Hits" section.

This approach also has merit, especially at the local level where amateurs may be confused with other radio services, or TVI has pitted neighbors against amateurs in administrative hearings. We do not believe that efforts to mobilize public support will be successful in defeating attempts of huge, wealthy industries who want to use spectrum for consumer devices that the public strongly desires.

The Industry Support Approach

A third direction to support amateur spectrum allocation is to obtain the support of industry. If industry is convinced of the value of amateur radio allocations, their voice may be raised in our defense when needed.

This approach can be especially powerful in the case of the technology oriented sector that may compete with amateurs for some of the same spectrum. If we have sympathetic people on the "inside," we can expect industry to take a more

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[3] The ARRL is "working with" supporters of future House spectrum management legislation to "ensure that the needs of Amateur Radio will be considered during the panel's deliberation." See page 16, QST, July 2002.

balanced approach to maintenance of our spectrum. If industry is convinced that many of the very best employees (and managers!) will come from the ranks of amateur radio oriented educational programs, they have a strong incentive to allow the amateur community unfettered use of the spectrum they currently have. While this approach has some of the same limitations as the other approaches (resources, numbers), we find that it offers a real anchor for the other approaches in that it provides a strong justification for the amateur allocation by itself: if we are working with industry at the cutting edges of technology, we are automatically providing a socially valuable service to the very parties we need to convince!

4. CUBESAT AS EXAMPLE

Engineering students at Cal Poly State University in San Luis Obispo have nearly completed the design, fabrication, assembly, and test of a picosatellite capable of testing small payloads in LEO. The first satellite to be developed at Cal Poly, CP1 will carry a recently developed sun sensor and is scheduled to launch from a Delta II in mid 2004. With CP1 nearly complete, the PolySat (Cal Poly's CubeSat) project is currently searching for a payload/mission and funding for the next generation picosatellite, CP2.

The satellites being developed at Cuesta and Cal Poly conform to the CubeSat standard, developed at Cuesta and Cal Poly in collaboration with Stanford University. The standard is simple, but defines the mechanical properties and interface requirements of the spacecraft. Currently more than twenty universities across the world are building to the CubeSat standard and that number continues to grow. CubeSats are cubes measuring 10cm with a maximum mass of 1kg. A key goal of the PolySat project at Cal Poly is to enable student participation in design and test of cutting edge technologies in space at low cost.

An Experience Report from the Trenches

Of course new, young hams are needed in every portion of the amateur service but especially so in the satellite service. There simply is no substitute for "hands on" best provided by mentors with experience. All too often with easy bulletin board availability, it is difficult

to determine the level of technical ability of the writer. In the CUBESAT world, available experience resembles an FM spectrum plot with a modulation index of 2.4, that is two large levels of experience that of the older mentor and the very well schooled student, but not much in between. The need for membership numbers during the survival years might be illustrated in this way. Dealing straight on with this seems paramount in the determination of a solution. Time is NOT on ham radio's side!! A demonstrable approach is the CUBESAT and the California Polytechnic University "hands on" mission. This concept is used in a number of schools taking leadership roles.

Cal Poly supports two, specific, goal orientated projects presently. The prime is the launcher within which all CUBESATS are placed. Each cube is limited to less than one kilogram (2.2 pounds) and 10 cm cubed (4 inch per side). Containers called "pea pods" of three or twelve experiments, launch each cube from the main launch vehicle. This task is taken very seriously noting all other experimenters depend on a launcher success. A functioning CUBESAT is also under construction. Most participants obtained first interest from a program at neighboring Cuesta College later transferring to Cal Poly. The first satellite is finished now completing shake table, thermo-vacuum and minor retrofitting. Ordinary off the shelf HT modules have proven workable in vacuum and temperature tests with minor component changes.

Again, the idea of two levels of skill is needed. Mentors are those in the amateur satellite program for many years some from the old Project OSCAR program in the 1960's, the grandmother of all amateur satellites. These individuals will bring a number of students to practical satellite applications in one weekend! That student may be pre-qualified in digital skills. Probably then our Bessel plot of available knowledge is not far off. Let us then limit comments to mentors and how they can best contribute. As hams involved with AMSAT there is an inherent appreciation of propagation and proper utilization of UHF radio hardware. Let the ham of experience carry on a bit about the old days, observing ducts, inversions, meteor scatter and yes, television interference too. CUBESAT will soon discover unwanted signals a replay of thirty year old interference problems. The same mentors often have the only "hands on" satellite station in the area or can arrange a

listening session. It is unimportant what feature or mode--CW, voice, digital just that a demonstration happens. In good time address getting started, operating, tracking basics, radio links, antenna requirements and comment on weak signal techniques. End with construction techniques now too small for tired eyes.

Older hams know a great deal about hardware by default. The mentor and student in combination results in a Commercial Off The Shelf (COTS) investigation team, the very key to CUBESAT procurement. One afternoon with the student at the keyboard and the mentor at the bifocals will produce a step function of knowledge for both. Hams reside everywhere and all companies, all disciplines, and all agencies are generally most willing to help if a specific request is made. These individuals are the key to donations, technical help so important to the creation and maintenance of CUBESAT programs. Just what have the students learned while developing a satellite experiment? In descending order of appearance:

Power Budget

With six sides of ten cm each there really is little radiant energy falling on the satellite to be recovered. The spacecraft rotates and experiences eclipses. At best, solar cells have an efficiency of twenty five percent. There must be some room allowed for antennas, sensors and mechanical attachments to the launcher. The conclusion is that CUBESAT has an appalling ONE WATT average DC power budget to work with! When a minimal 330 milliwatt 436 MHz transmitter consumes twice that, a few dozen CUBESATS transmitting intermittently should not cause much interference to ground stations.

Thermodynamic Calculations

Of immediate concern was the realization that there were few, if any, thermodynamic models of boxes this small covered with questionable thermal radiators. A number of phone calls resulted in more questions than answers even when good guesses were requested. Quite a number of good computer models were found but the result was that the internal battery temperature could not be predicted to within 20 degrees C under any set of conditions.

Battery Selection

Here was a real challenge. Battery technology is moving faster than the web pages that advertised them. Further, few manufacturers care to comment on survivability under gross depressurization during launch and sustainability in orbit. The design team had a major decision to make while simultaneously noting that both primary cells and rechargeables need be designed. Recharging appeared hopeless at first. Simply placing primary cells in orbit would eliminate the need for a control system, so advised the IARU. Eventually a design evolved using two battery sources, one being used to power the command system when the main unit became discharged. A highly efficient switching regulator was designed with low voltage cutoff, which promptly interfered with the command receiver. Dual transceivers with antenna switching are now used.

Antenna Deployment

A severe problem to be solved is an antenna system to be placed on a four inch cube. Metallic measuring tape unfolding upon command works. CUBESAT duplicated that but painted one side white, the other black to cause some rotation in sunlight. But what if the fishline holding the tapes fails to part when commanded? A small hands on experiment was conducted. Various strengths 2,4,8 pound of fishline was arranged to hold the antennas in place while UV irradiated the fishline which eventually allowed the antennas to deploy! Four pound line of the worse possible manufacture works the best. To this day we are not sure how good a radiator this system might be. Cuesta College built a fully non-metallic rotating support in which a cube is held as a simulated antenna range. Nothing beats an anechoic chamber and proper antenna range.

Stamp Programming

Three students - one full time - were required to get an internal control system operating reliably with constant changes due to more knowledge being gained each day. Some creative test equipment was developed. Here is an example: Two function generators were arranged. one simulating satellite spin while another programmed for 90 minutes simulating orbital period. A third programmed various levels of occultation. All three were operated to determine the optimum switching level via a stamp. Now program this device to include a

failure recovery system, which must be done as best demonstrated by AO-7 recovery after many years of sleep. This became a rough task because only a few milliamperes of consumption were allowed.

Component Selection

The group has been asked how we were able to make a less than commercial grade ham HT survive temperature and vacuum. Of course all aluminum capacitors must be replaced with tantalum. Components must be vacuum tested preferably in equipment owned by the project. The physics department was most unhappy when we coated the inside of their bell jar and pump with component splatter. For cold measurements start with dry ice. Progress to liquid nitrogen within a chamber. Use what you have on hand, vacuum cleaners, sun lamps, UV lamps. Paint can mixers at the hardware store make great trial shake tables. Do not be afraid to ask questions of anyone, even mentors! Manufacturers often will provide [a] components if you will test them, again a mutual benefit to both.

Final Test

There is no such thing as "final" test other than the project leader demanding that all fingers are to be removed NOW! There is no "clean" room clean enough nor a design tested enough nor enough calculations made. The members have reached the point where they know each other better than their mothers while each day more questions are created. If a flight ready model is ever achieved. put that in a bag while considering building a spare and document each move. Use an audio tape recorder editing out the continual "I'll never do a fool thing like this again." There is no final exam like FINAL TEST nor any greater pleasure than mating ham radio with hands on CUBESAT learning experience.

Summary of Benefits of CubeSat Approach

The CubeSat program exhibits the following benefits:

o   Students experience the entire lifecycle of mission (design, analysis, fabrication, assembly, test, integration, launch, operation, tracking, communications by amateur radio, failure analysis).

- Students work in and manage teams of engineers and non-engineers mentored by amateur radio operators and industry engineers.

- CubeSat development and launch is inexpensive, even compared to typical university microsats. Amateur radio provides an inexpensive way to communicate with the satellites and access to a worldwide network of volunteer monitoring stations.

- CubeSats encourage innovative design approaches to meet mission requirements with limited resources: using commonly available off-the-shelf amateur radio and computing hardware.

- Students interface professionally with members of industry and experienced amateur radio operators, many students obtain their own licenses[4] and become mentors for entering students.

- All of the engineering students involved in the project are exposed to the use of Amateur Radio for satellite communication, and to mentoring amateurs in their daily work. Most, if not all, of these students (have or) will go on to employment as engineers in the aerospace and consumer communications industries.

Notice that most all of these benefits dovetail with our desire to preserve amateur spectrum allocation by showing the social value of Amateur Radio activities to the very industries who have the greatest influence on spectrum decisions. Incidentally, the other approaches are supported by these activities in an indirect way.

5. CONCLUSIONS

ARRL and AMSAT are good political avenues but the need is to get closer to industry rather than farther away. CUBESAT, [as an example,] using commercial off the shelf (COTS) material

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[4] This year we've generated about 20 new hams worldwide among the engineering students who volunteer their time for the project. Some have become hams and gone on to employment as graduate engineers from the past year.

with highly qualified hams, provides a reasonable impact upon the space industry.

A major weakness must be recognized. Ethically, CUBESAT is walking a thin line between amateur radio usage and commercial interests via the funding of student projects. While this is not new to ham radio the solution must be a partnership with a proper set of guidelines in place such that this asset is of mutual benefit.

REFERENCES

General info: www.polysat.org and www.sloradio.net

CubeSat and PolySat project description at: www.csc.calpoly.edu/~csturner/sat.paper.pdf Further information can also be found at www.sloradio.net

Sample OSCAR reference:

W.Orr, "The OSCAR III VHF Translator Satellite", QST Feb 1963.

BIOGRAPHIES OF THE AUTHORS

Cliff Buttschardt holds an amateur extra since 1963. He was first licensed in 1948 and now holds lifetime memberships in Project OSCAR, AMSAT and ARRL as an A1 operator. Cliff retired full time teaching, to become a CUBESAT mentor and instructor in the San Luis Obispo, CA area. His original satellite association was with Project OSCAR in 1964 and the construction of OSCAR III. He is an AMSAT coordinator, while operating all active satellites as K7RR or W6HDO.

Clark Savage Turner, J.D., Ph.D. holds the Amateur Extra Class license and has been licensed since 1968. He is an attorney and software engineering professor at Cal Poly State University in San Luis Obispo, CA.

Environmental Factors Affecting AO-40 Reception

G. Gould Smith, WA4SXM

Abstract

AO-40 has forced many amateur satellite operators to become knowledgeable about equipment and operation in the frequency spectrum above 70 cm. As we learn to operate on S-Band and K-Band we find out that "We are not in Kansas anymore." The trip is an interesting one because principles and theories that have not played an important role in operating the lower frequencies not become incredibly important. AO-40 has presented us with a golden opportunity to learn more about higher frequency operation and theory. As we become familiar with S-Band operation, we can now see the benefits of the vast bandwidth we have there and begin to explore new ways to make the most use of it.

Background

After purchasing and mounting a new K5GNA 2.4 GHz receiving system, I got up at 4am to operate, there was single digit squint and I heard nothing. I tired an hour later and could barely hear the beacon, but couldn't even see peaks using AO40Rcv. Tried again later with squint into the teens and the signal boomed in. What was going on? Through the years I had noted a slight reduction in signal strength while operating the digital satellites and shooting through the trees. This hadn't caused me noticeable data lose because I was using high gain antennas. Also there was no noticeable difference over many years working AO-10 or AO-13 during different times of the day or in the summer and winter. Why did the beacon all of a sudden get strong? Other than the frequency - What is different here? ANSWER – 2.4 GHz and the trees. This led me to this investigation and to this paper.

AO-40's orbit

First let's look at the orbit of AO-40 and the advantages and challenges it presents. Using InstantTrack V1.54 and writing the ephemeris output to a file do a 4-5 day sequence of tracking of AO-40, import this into Excel, sort by azimuth and elevation, then plot. The loops are the perigee part of the pass, so these can be ignored or edited out. Specifics to do this operation are found at the end of the paper. Figure 1. shows the basic arc that AO-40 follows for latitude 36° N in the eastern US (Knoxville,TN).
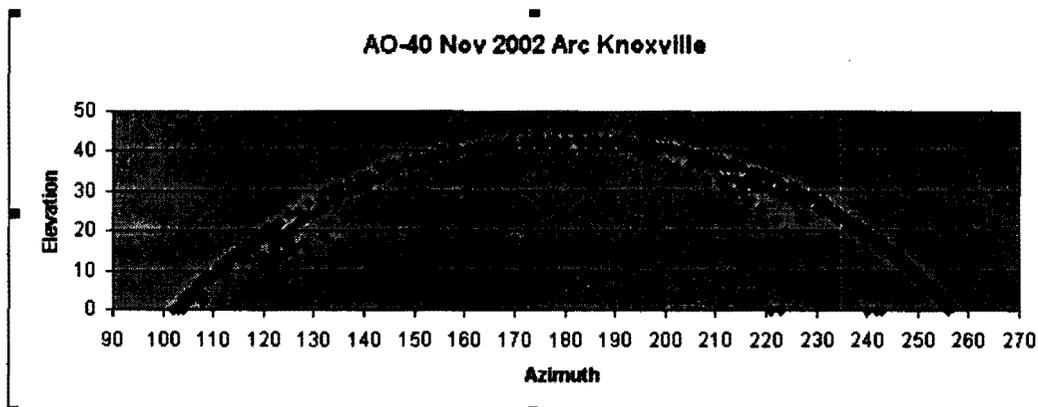

Figure 1. Basic AO-40 tracking arc for mid-latitude US

How does the AO-40 arc change over time?

I redid the data gathering and plotting in two month increments for the next year. This data in the table below shows that the orbit arc remains basically the same. It will move ±10° in azimuth and elevation over the next year. **The important fact is that people in the US have an East to West arc with the peak of the arc to the South.** Any environmental factors West to East through North will have no effect. Those with environmental obstructions due South will pose less of an obstacle because the satellite is at its highest elevation (30-50°). The east and west part of the arc pose the most challenge as far as environmental obstructions, as the elevation goes to or comes from 0°.

For Knoxville the upcoming maximum elevation changes are:

July 2002	43°	March 2003	48°
September 2002	42°	May 2003	50°
November 2002	43°	July 2003	53°
January 2003	45°	September 2003	55°

How different is the AO-40 arc in different areas of the US?

Since AO-40 is in somewhat of an equatorial orbit you would expect stations as they are further North or higher latitude to have a lower overall elevation angle. This is the case.

city	Lat	Long	Max El	Az range
San Antonio,TX	29.424	98.5	50	100-259
Knoxville,TN	35.93	84.04	43	102-256
San Jose,CA	37.338	121.893	42	103-257
West Harford,CT	41.715	72.727	37	104-253
Bismark,ND	46.808	100.78	30	106-253

Figure 2. Representative arc of the AO-40 orbit for various locations across the US

AO-40 Az/El Nov 2002 West Hartford, CT
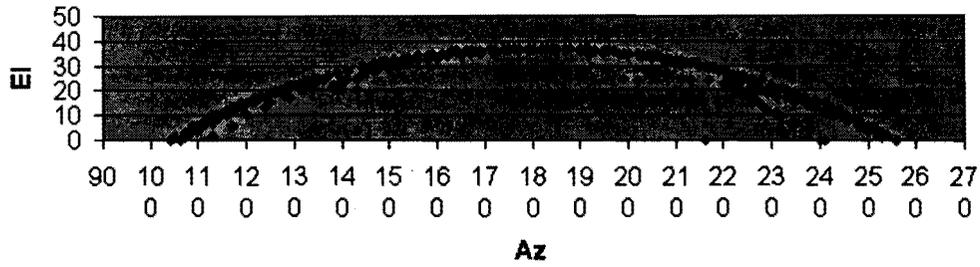
AO-40 Az/El Nov 2002 San Antonio
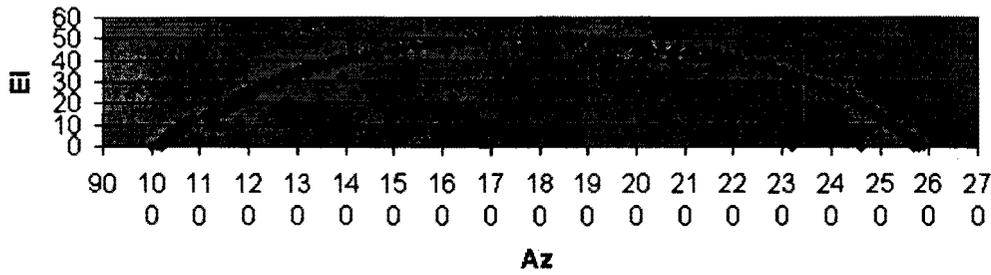
AO40 Az/El Nov 2002 Bismark,ND
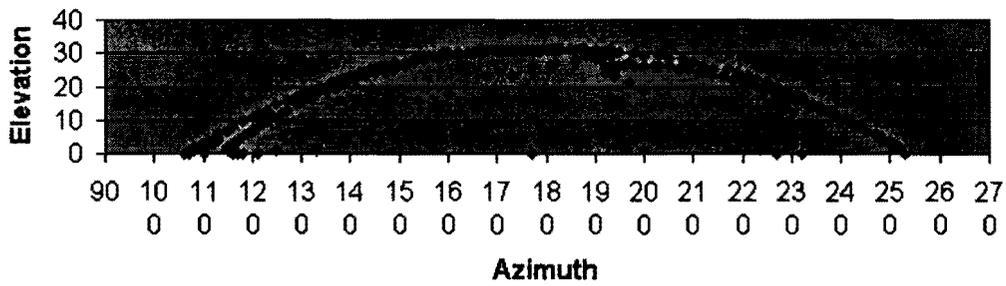
AO-40 Az/El Nov 2002 San Jose
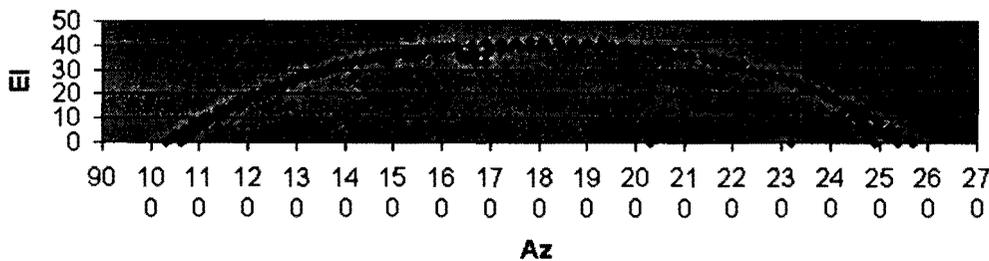
The AO-40 track through the sky changes very slowly, relative to the LEO satellites, except around perigee. This change is 1-2° in both azimuth and elevation every 11 minutes. The fact that its' location in the sky changes means that the satellite will eventually move over obstructions, unless you live in a very satellite challenged area. An interesting note from Figure 3, the azimuth changes fastest around apogee and the elevation changes least. This is a classic example of Kepler's second law says that the orbit must carve out equal areas for equal periods of time.

Figure 3. AO-40 Az/El tracking rate of change
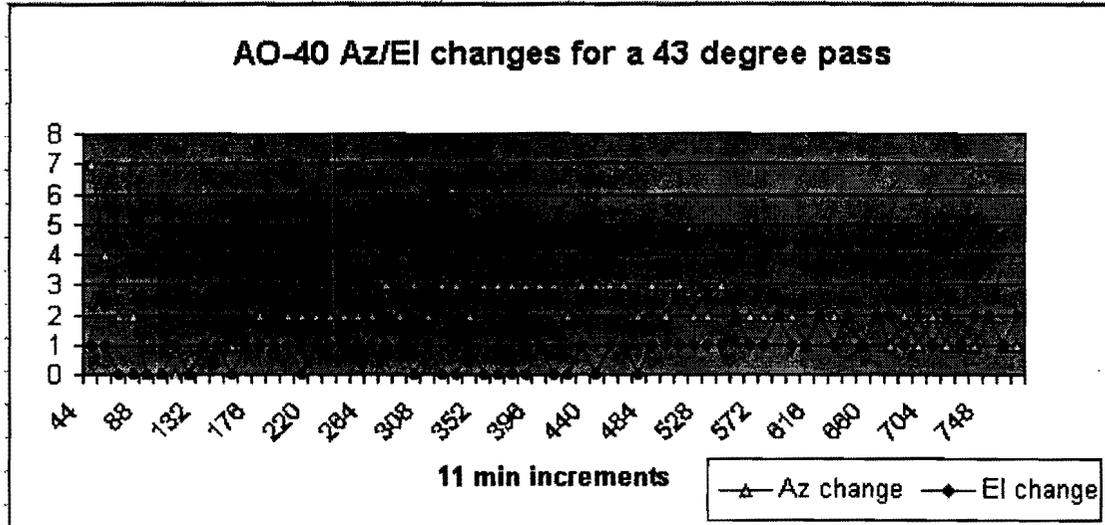
What environmental factors are working against me receiving AO-40 ?

- Distance
- Cosmic noise
- Atmosphere
- Mountains and Buildings
- Rain, Dust and Sand
- Trees

Let's look at the effect each of these environment factors has upon AO-40 reception. This section uses descriptions of the signals in terms of wavelength, frequency and band interchangeably. To help cross-reference these I have included a chart at the end of the paper.

Distance

Free Space Loss formula

$$L_{FSL} = (4\pi\,R/\,\lambda)^2 \quad \text{R is distance, } \lambda \text{ is operating wavelength}$$

Converting to frequency and dB the equation becomes:

$$L_{FSL\,dB} = 92.4 + 20\,\log f + 20\,\log R$$
f is frequency in GHz, R is range in km

Table 1. Path loss at various distances in the AO-40 orbit:

Path Loss in dB				
		70cm		
Distance km	2.4 GHz	0.435 GHz	1.2 GHz	25 GHz
1000	160.12	145.17	154.47	180.36
10000	180.12	165.17	174.47	200.36
20000	186.14	171.19	180.49	206.38
30000	189.66	174.71	184.01	209.90
40000	192.16	177.21	186.51	212.40
50000	194.10	179.15	188.45	214.34
60000	195.68	180.73	190.03	215.92

Gene Marcus, W3PM has included path loss in his exceedingly useful spreadsheet program that computes the anticipated signal strength of the AO-40 beacon. Of course the hardware used to capture the signal and get it to the receiver are the most important part in recovering as much of this signal as possible. This spreadsheet can be found at:
http://home.hiwaay.net/~mmarcus/download/ao40.xls

Cosmic noise

Stars or other bodies behind the satellite generate noise at multiple frequencies that compete with the signal from the spacecraft. The noise is defined in degrees Kelvin and called Sky Temperature. The Nova for Windows program has a sky map that shows what background noise to expect when pointing at various points in space. The map only shows noise temperatures for 50, 130 and 400 MHz. Generally the VHF bands have higher noise temperatures than S band.
InstantTrack in the text mode will show the background sky temperature (TSky), if the 2.4 GHz beacon frequency has been added. Usually this shows up as 3° K.
Gene's spreadsheet also includes this value in his calculation, which defaults to 8°.
The 'Radio Amateur's Satellite Handbook' has a conversion chart of TSky to dB.

Figure 4. Nova for Windows Sky Temperature map for 400 MHz
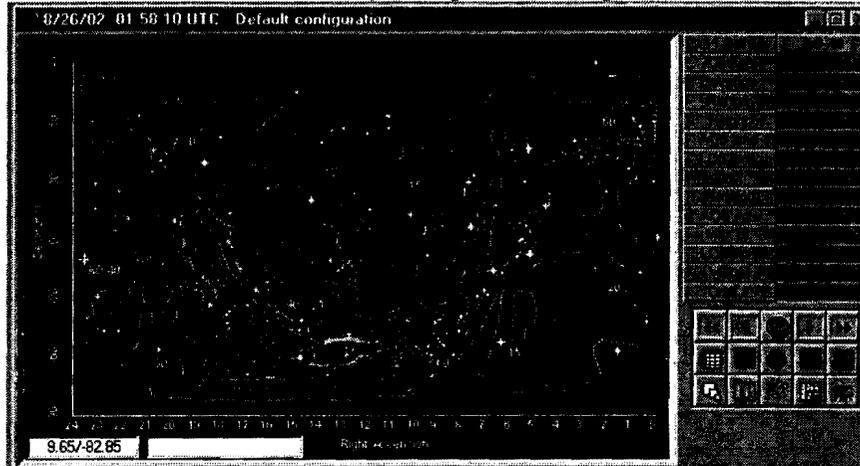
At higher elevation angles the TSky noise is a generated by the heavenly bodies. As the elevation angle approaches the horizon the noise originates from reflections off the terrain and side lobes.

Atmosphere

The earth's atmosphere only allows certain frequencies to pass through it. Figure 5 shows the electromagnetic spectrum and which frequencies make it through the atmosphere. Note that there are only a couple of windows for this energy, one for visible light and one for VHF to cm microwave signals.

Figure 5. Electromagnetic spectrum with RF windows
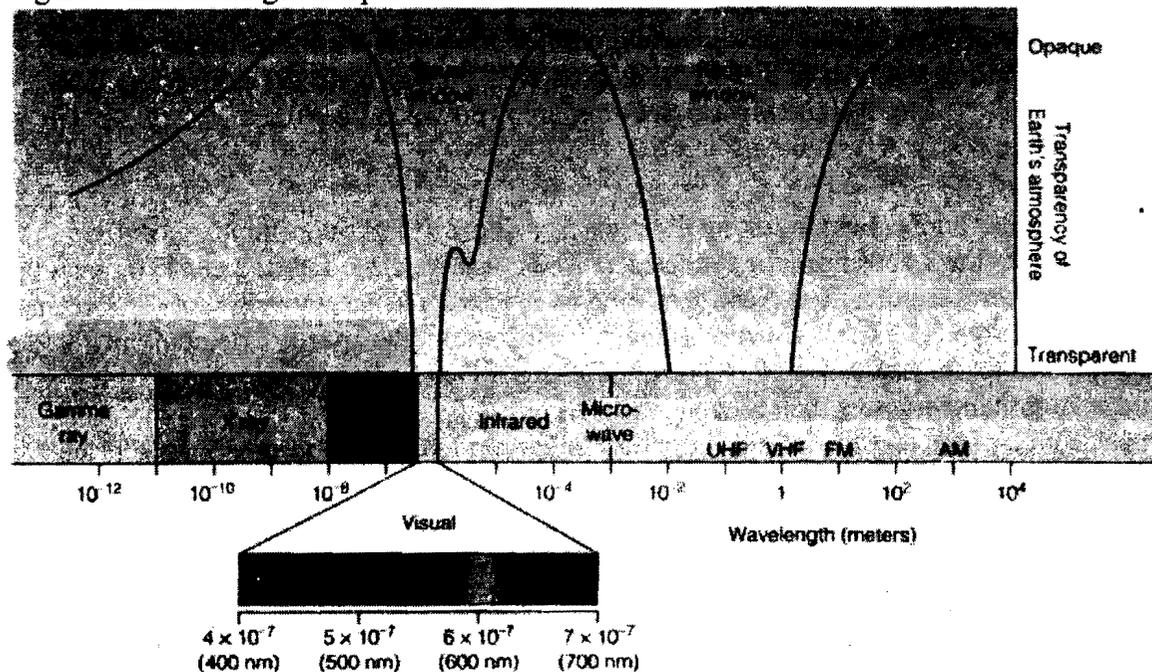
Atmospheric absorption at 2.4 GHz is minimal, but at 24 GHz there is a resonance for water vapor and one for oxygen at 60 GHz.

Mountains and Buildings

Understandably these pose quite a challenge to reception and essentially shield the 2.4 GHz signal. Kulemin found that a 23cm brick wall would attenuate a 3 GHz signal 12 dB and this quickly rose to 46 dB when the brick was wet. The reflections off of these objects do cause strong signals to be received in places far from line of sight. For a fixed location signal this could be of great benefit because a decent signal could be obtained by finding the reflected signal. For satellite signals that are constantly changing location this would pose quite a challenge to track the reflection. As the satellite angle changes you will also get a benefit as it skirts the edge of an obstruction which causes the signal to diffract over the edge and provide coverage where there is no line of sight signal. Alas, for satellite operation this is only temporary, as the angle changes this effect is lost after only a short time.

Rain, dust and sand

Rain has been recognized as a cause of unwanted signal attenuation in the millimeter wave region (3 to 30 GHz). Its' effects vary depending upon the drop size and the rate at which the rain is falling. Higher GHz frequencies are more affected than the lower GHz ones because the drop size approaches the wavelength of the signal. Raindrops are generally on the order of 0.05 cm to 0.7 cm. **Rainfall has proven to be inconsequential in the 2 GHz band,** but becomes increasingly significant as the frequency increases. At 11GHz rainfall imposes a severe attenuation upon the microwave signal. For more specific information check the Medhurst paper.

Dust and sand storms research has seen a rise in the last decade due to the Gulf war. Sand storms and dust storms are two quite different phenomena. What often occur in arid regions of the world and are referred to as sand storms are actually dust storms. Dust clouds of very dry soil often rise >1km into the air and obscure the sun for long periods of time. Sand storms seldom rise more than 2 meters above the ground due to the higher density of the sand. Most often at head level above the sand storm the sky is clear and the sun shining. Since the dust and sand particles are many times smaller than the signal wavelength they tend to be insignificant, on the order of 0.5 to 1 dB, for most of the UHF and SHF bands. Additional specifics can be found in the Comparetto paper.

Trees – The Foliage Effect

Those of us with trees around the house/shack have met our greatest obstacle to AO-40 reception. There have been a number of studies done over the years for military reconnaissance and satellite reception to determine how much absorption trees consume. Quite a number of the studies differentiate between absorption and reflection of the signal. For our purposes we are only interested in the result, how much gets through the foliage. Lately there has been quite a bit of interest in tree absorption/reflection studies because of the growth of wireless networking, the 802.11 standard at 2.4 GHz. Corporations and neighborhoods are interested in sharing a high speed connection using RF networks.

The general consensus of the literature is that the shadowing from the canopies of one to two trees is the major contributor to the attenuation experienced. Signal fading results from the scattering and absorption from both branches and foliage.

Static measurements of attenuation due to isolated trees has been performed at UHF, L-Band, S-Band and K-Band by Benzair et al.[1991], Butterworth [1984], Cavdar et al. [1994], Vogel and Goldhirsh [1994,1993,1986], Vogel et al [1995], Ulaby et al. [1990] and Yoshikawa and Kagohara [1989]

Table 2 lists the measured attenuation of specific trees at 870 MHz. All trees were in full foliage. Those with an * were measured in VA and those without were measured in MD. The attenuation coefficient is to be used with trees of similar makeup and of different sizes. Take the coefficient and multiply it times the depth of the tree foliage. Note the great diversity in the Pin Oaks.

Table 2. Summary of single tree attenuation @ 870MHz from Vogel and Goldhirsh

Tree Type	Attenuation (dB)		Attenuation Coefficient (dB/m)	
	Largest	Average	Largest	Average
Burr Oak*	13.9	11.1	1.0	0.8
Callery Pear	18.4	10.6	107	.1.0
Holly*	19.9	12.1	2.3	1.2
Norway Maple	10.8	10.0	3.5	3.2
Pin Oak	8.4	6.3	0.85	0.6
Pin Oak*	18.4	13.1	1.85	1.3
Pine Grove	17.2	15.4	1.3	1.1
Sassafras	16.1	9.8	3.2	1.9
Scotch Pine	7.7	6.6	0.9	0.7
White Pine*	12.1	10.6	1.5	1.2
Average	14.3	10.6	1.8	1.3
RMS	4.15	2.6	0.9	0.7

Measurements made by Cavdar et al. in Turkey in 1993 show the average attenuation and attenuation coefficients are similar at UHF and at L-Band. These can be seen in Table 3.

The ITU-R [1994] measured long path(ground to ground) and short path attenuation (ground to ground or slant path through the foliage of a single tree with foliage depth of 10-15 m). **The study concluded that short path attenuation coefficients were between 1-2 dB/m at frequencies between 1 and 4 GHz.**

For a medium size tree figure :   **10.5 dB at UHF**
                                                    11 dB at L-Band
                                                    18 dB at S-Band
                                                    23 dB at K-Band

Table 3. Cavdar et al. Tree Attenuation at 1.6 GHz

Tree Type	Average Attenuation (dB)	Attenuation Coefficient (dB/m)
Willow	10.45	1.1
Pine	18.0	1.8
Linden	9.1	1.4
European Alder	7.0	1.0
Acacia	6.75	0.9
Popular	3.5	0.7
Elm	9.0	1.2
Hazelnut	2.75	1.1
Maple	16.25	1.25
White Spruce	20.1	1.75
Laurel Cherry	12.0	2.0
Plane	16.9	1.35
Fir	12.75	1.5
Fruit	9.6	1.2
Average	11.0	1.3
RMS	5.1	0.35

Attenuation of trees in leaf and without leaves

Measurements done at 870 MHz show that attenuation due to full foliage is 35% larger than the corresponding attenuation for the tree without leaves. This suggests that the predominant attenuation at 870 MHz arises from the tree branches .

At L-Band the measurements show again that only 15% additional attenuation due to foliage. At K-Band (20 GHz) the wood and leaf parts of the tree are both important showing increases due to foliage from 2 to 3 times.

At 2.4 GHz- **the wood part of the tree is the major contributor to attenuation.**

Measuring attenuation between 1 GHz and 4 GHz

Benzair et al. found that full foliage deciduous trees at frequencies between 1 and 4 GHz would obey this relationship:

$$MEL = 079f^{0.61}$$

where MEL is mean excess loss or mean attenuation coefficient in dB/m and f is frequency. This is about 1.5 dB/m at 2.4 GHz.

Determining the attenuation due to foliage

So determine the distance through the tree(s) and multiply by 1.5 to get the dB attenuation of the tree(s).

A maple in my yard is 38' thick which means that it attenuates the 2.5 GHz signal :

38' * 12" per foot / 39.37" per meter = 11.58 m * 1.5 dB/m = **17.37 dB**.

One heck of an attenuation before it gets to the antenna.

Table 4. Sample 2.4 GHz tree attenuations for trees with general foliage depths:

10' thick tree → 4.5 dB
15' thick tree → 6.8 dB
20' thick tree → 9.1 dB
25' thick tree → 11.4 dB
30' thick tree → 13.7 dB
35' thick tree → 16.0 dB
40' thick tree → 18.3 dB
45' thick tree → 20.6 dB
50' thick tree → 22.8 dB
55' thick tree → 25.1 dB
60' thick tree → 27.4 dB

Determining Your AO-40 visibility window
Generate an AO-40 plot using Excel then go outside and determine the elevation and azimuth that various obstructions caused by trees, buildings and mountains east to west through south. Plot these against your AO-40 arc and result will show you when you can use the satellite effectively. See Figures 8 & 9 for sample plots.

Here are three ways you can determine the elevation of the obstacles.
1) Trigonometry
2) Inclinometer
3) Camera mounted to your antenna boom.

1. **Use trigonometry** to determine the elevation angle of the obstruction.

$$\tan\theta = \text{opp/adj}$$

θ 60 adj opp
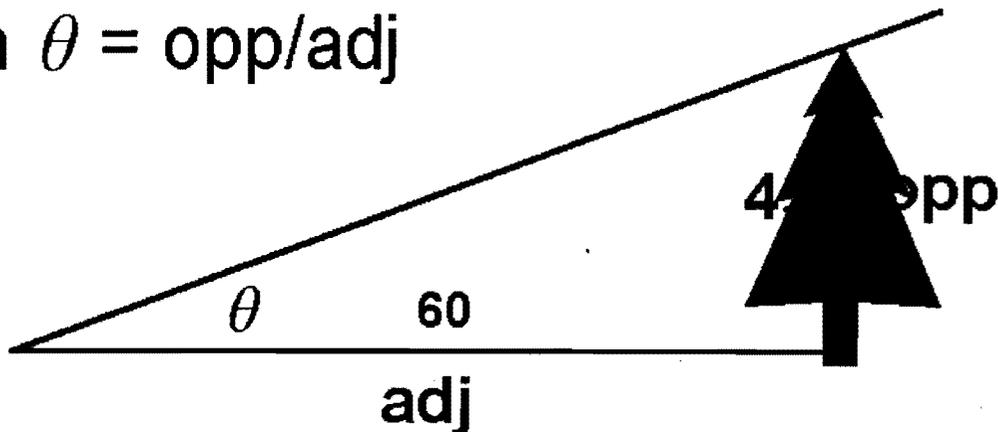
$$\tan\Theta = 45/60$$
$$\tan\Theta = .75$$
$$\Theta = 36.8°$$

2. Use an inclinometer (mechanical of electronic)

Tom and Ray of NPR's Car Talk made a very clever observation a few months ago and one that fit right in with my philosophy –'Look at every home project as an opportunity to buy a new tool.' The mechanical one I found at The Home Depot for about $4.95, the electronic one is a bit more expensive at $120. Of course there is the $0.25 protractor and string.

Figure 6. Mechanical and electrical inclinometer
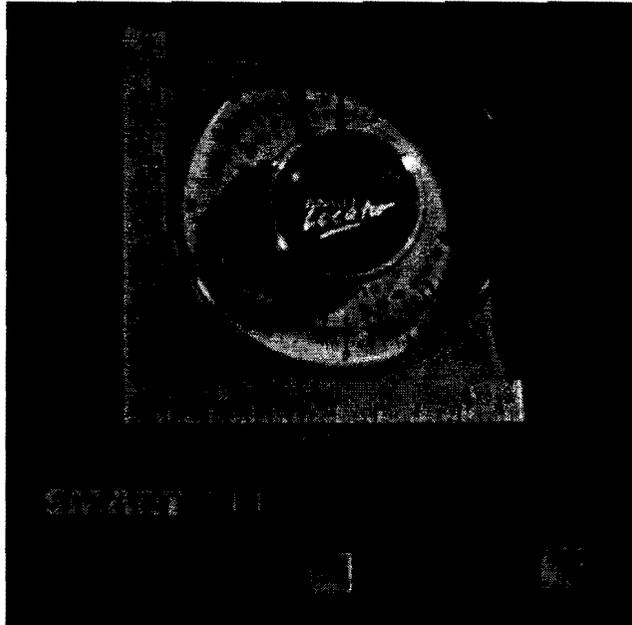
Figure 7. Using the inclinometer to determine the angle to the top of the trees
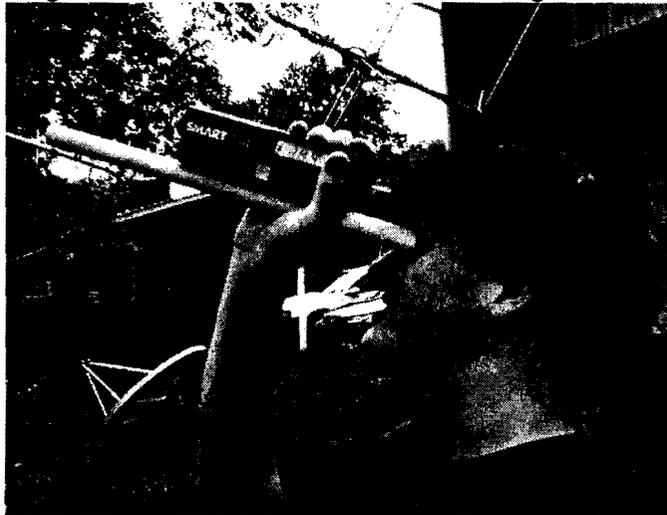
3. Mount a camera on your boom and move the rotor while observing the trees, buildings and mountains then record the Az/El and put this on your plot of the AO-40 arc.
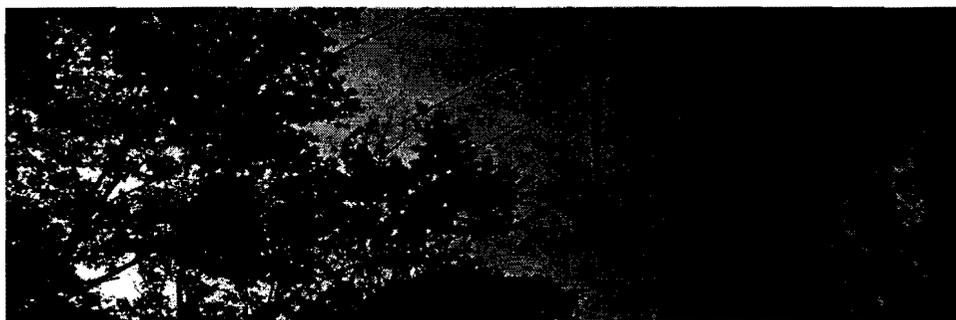
Improvements and Solutions

1. Cut the trees – NOT always the best solution, especially if they are not yours.
2. Increase the height of your AO-40 downlink – this reduces the angle.
3. Move the antennas farther away from the trees to give you less of an angle to the top of the tree.
4. Best of all move the antenna back and up, this will do the most to reduce the elevation effect of the obstructions.

Figure 8. Original antenna view of AO-40 arc at WA4SXM
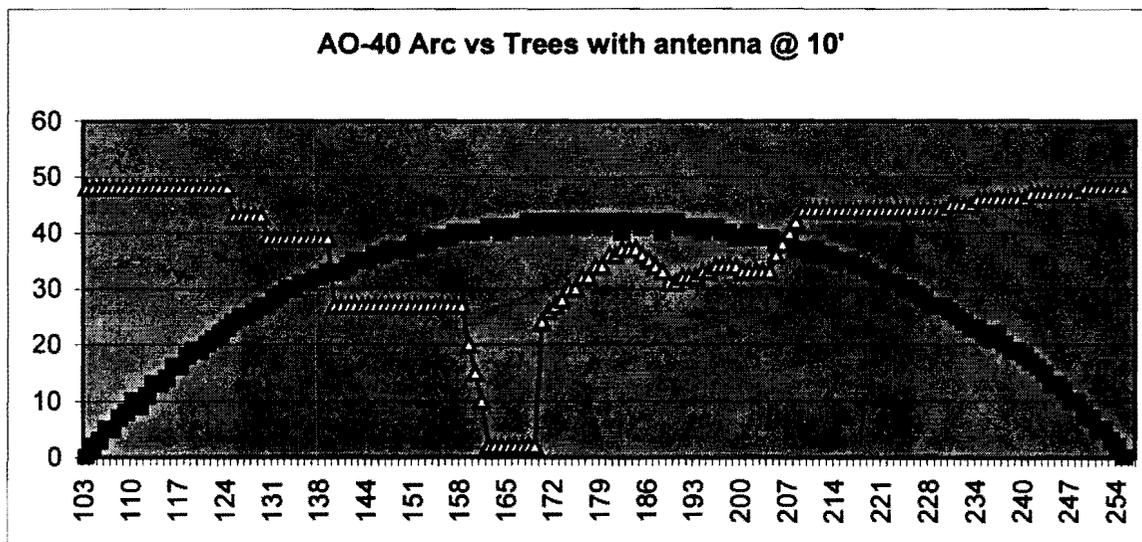
You can see from Figure 8 that I had a very restricted view of the satellite. In fact I could only work it from azimuth 140° to 206°, quite a restriction.
To improve my situation, I moved the antenna system up on to the roof, and attached it to an iron plumbing vent. The antenna went from 10' off the ground to about 23'. This made a significant improvement in my AO-40 visibility.

Figure 9. The improved visibility with the antenna at 23'
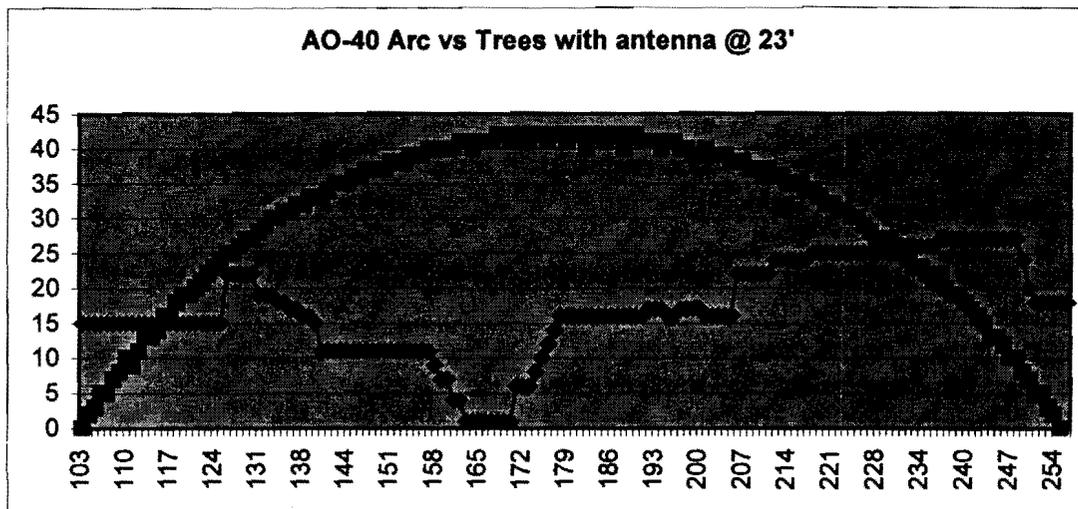
I now can work AO-40 from 117° to 232°. My range went to 115° as opposed to the 66° with the antenna at 10'. This is a marked improvement.

Conclusion: Foliage has a dramatic attenuation effect upon the AO-40 2.4 GHz signal, optimize your antenna placement to get the best view of the AO-40 arc.

InstantTrack to Excel plot procedure to graph the AO-40 Arc

Run IT
Select #3, Ephemeris
Select a date and AO-40
Once the first screen appears, hit the F key for save the data to a file
Enter a filename, I use the format AO40MMYY.txt
Hit the ENTER key 7 or so times to get 5 or 6 days worth
Hit the F key again, note the filename in the upper right disappears and the file closes

Open Excel
Under File, select Open
Goto your IT subdirectory
Select All Files (not just .xls files) and click on the text file you just saved
This opens the Text Import Wizard
    Select the Fixed Width, Start import at row 1, File origin Windows (ANSI)
    Step 2 of 3 should be good, click NEXT
    Step 3 of 3, click DATE to select the DATE type for the date data - FINISH
Now the data has been imported into your spreadsheet

Select column C, then under EDIT, select REPLACE
    By Find what: type /
    By Replace with: *enter nothing*
    Click on Replace All

Delete row 1 (satellite #, AO-, and 40)
Highlight the entire data
Select Data, Sort
Sort by: Azim   Ascending
Then by: Elev   Ascending
Click OK
Now multiple days data has been sorted such that all the azimuth values between ~90 and ~270 degrees and their corresponding elevation values are together

Goto the bottom of the spreadsheet and delete the pass delimiter lines (highlight the rows, then select edit, delete)
Highlight columns C & D (Azim and Elev)
Goto the top toolbar and select the Graph Wizard
Select XY (Scatter), sub type - just the points, no connecting lines NEXT
Data range and series should be good, click NEXT
Fill the Chart Options data
Chart Title: whatever you wish to call it - ex. AO-40 May 2003 Arc
Value (X) axis: Azimuth
Value (Y) axis: Elevation
NEXT
Select As an object in (worksheet name) - FINISH
Click on the graph and extend the horizontal size about 11 columns
Right click on the X-axis label and select FORMAT axis
Uncheck the AUTO checks for all boxes ·
Enter the new axis data
Minimum 90
Maximum 270
Major unit 10
Minor unit 5
The hooks in the graph are the perigee part of the pass when the satellite is rapidy moving and taxing to track, you can clean up these by removing the rows that contain small elevation data compared to other elevations around it. The 16 and 17 elevations can be removed since the other elevation data is 46-50 degrees.

Date	Time	Azim/	Elev
17-May-03	1728	182	50
16-May-03	1601	183	46
20-May-03	1008	184	16
20-May-03	1600	185	47
17-May-03	1739	185	50
21-May-03	1729	185	50
16-May-03	1031	186	17
16-May-03	1612	186	46
17-May-03	1750	188	50
21-May-03	1740	188	50
20-May-03	1611	189	47

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Frequency   Wavelength Band

300 MHz ———————— 1 m

| 435 MHz 70 cm |

UHF

| 1.2 GHz 23 cm |

10^9 Hz = 1 GHz ·········

| 2.4 GHz 13 cm |

30 cm
L-Band

3 GHz ———————— 10 cm   15 cm
S-Band

8 cm

10^{10} Hz = 10 GHz

SHF

C-Band

4 cm

2.5 cm X-Band

25 GHz 1.3 cm

30 GHz ———————— 1 cm   0.75 cm K-Band

10^{11} Hz = 100 GHz

EHF

300 GHz ———————— 1 mm

101
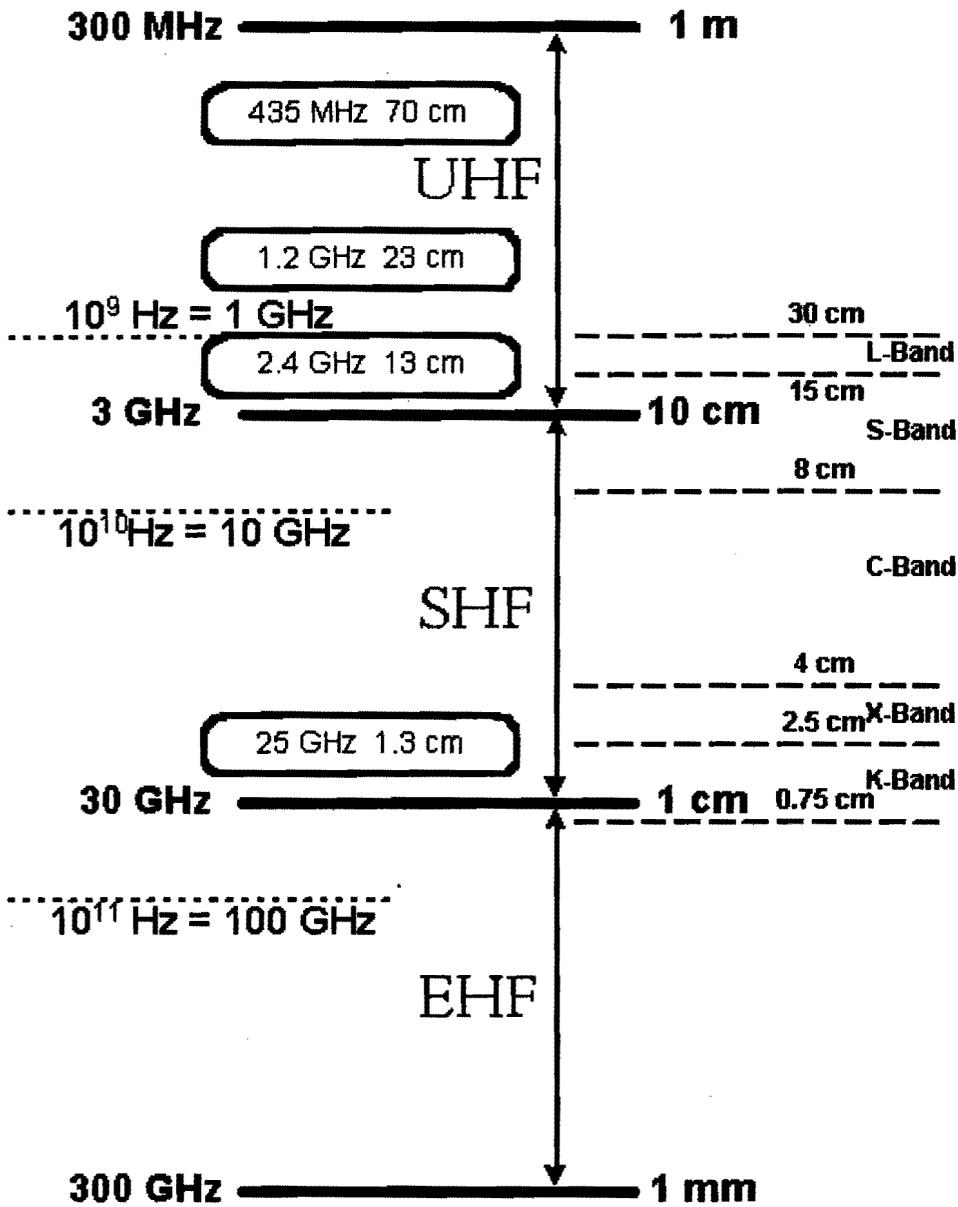
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The P5 Special:
A Satellite Station for North Korea

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One of the most-sought HF DX stations in years is operated by Ed, P5/4L4FN. The 15 and 20 meter bands are jammed with hopeful DX-ers whenever he operates. Bruce Paige, KK5DO, is the QSL manager for Ed's operation and has been in constant contact with him via email (1). As a fortunate coincidence, Bruce is also an avid amateur satellite operator. Before Ed even had his amateur radio operating permit from the Republic of North Korea, Bruce was talking about getting P5 on satellite—specifically getting Ed on AO-40 and nabbing one more country for satellite DXCC. What a coup that would be! Was it possible? What would it take to accomplish this feat?
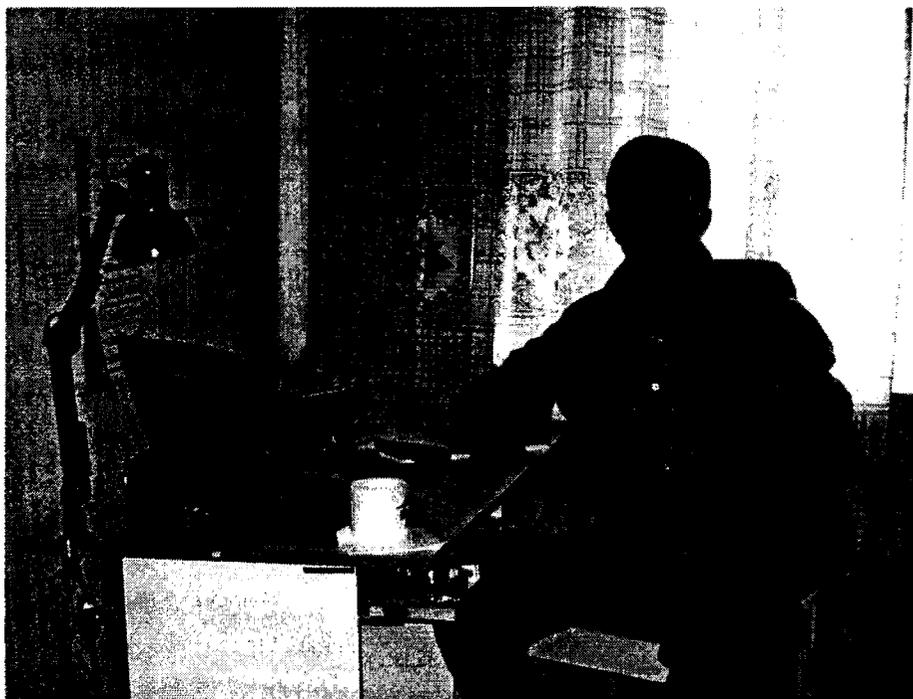
Figure 1 - Ed, P5/4L4FN, At The HF Controls

The Mission
The conversation about a P5 satellite station started in late 2001—about the time it was announced AO-40 would "hibernate" for the winter. At that time no one really knew what to expect from the satellite during the winter, so the planning effort did not move much beyond the talking stage. As the winter progressed and it became apparent the satellite was perfectly usable, we began discussing construction of a system that would be operational when AO-40 returned "normal" ALON/ALAT orientation.

Satellite Groundstation?
Ed's HF station is quite modest: an ICOM IC-706 MKIIG, a small beam, and an HF vertical. This would be a rough, but not impossible, starting point for an AO-40 capable station. He had the 2 meter band suitable for the S-band downlink to utilize a surplus MMDS converter. He also had the requisite 70 cm band for the uplink, but power was limited to 20 Watts. The shopping list developed

into: an S-band downlink antenna and downconverter, a U-band uplink antenna, a diplexer for the IC-706 common V/UHF port, and miscellaneous cables, adapters, etc. for a plug-and-play system. We needed to ship every single cable and adapter, since even the most seemingly common items may be difficult to locate in North Korea.

Even when fully configured for mode U/S, this station will not be full-duplex. Ed will not be able to hear his return signal. K5OE has successfully worked many satellites with a similar setup using a similar radio, an FT-100, in SPLIT mode. We opined we could set up an administrative procedure for Ed and the operators on the other end to make this situation workable. In effect, we plan to have Ed fix his uplink frequency and then listen across a predetermined frequency range for responding stations.

S-Band Antenna

This project has some unique difficulties, not the least being the need to have a shipable antenna system. An Arrow Antenna, with its split boom and disassembled elements, was an easy solution for the UHF uplink. But what about an S-band dish? To that end, a small and light receive antenna was desired, but with the maximum gain possible in a small package. K5OE donated a TSI 3733 downconverter and K5GNA donated a 2 foot MMDS dish (2). Figure 2 depicts the 2 foot dish, as received from K5GNA with K5OE's TSI 3733 downconverter installed (sans feed reflector). K5OE installed the K5GNA Murata filter mod in the 3733 and the unit bench-tested at 34 dB gain and 1.1 NF at 123 MHz.
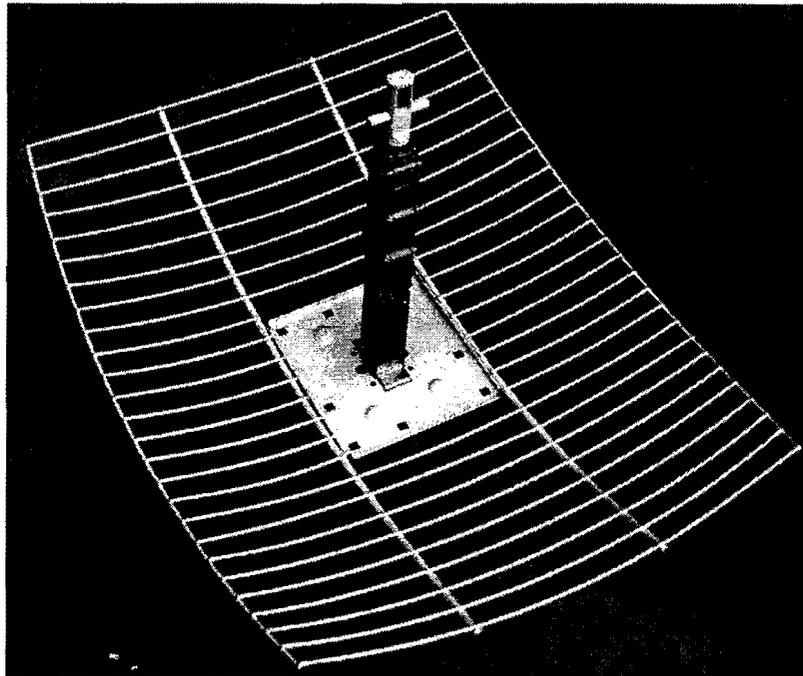

Figure 2 - K5GNA 2' Dish and TSI 3733 Downconverter

This dish was then "converted" for circular polarization using some #10 AWG wire and covered with aluminum mesh screening material commonly available from the local hardware store (3). This "conversion" to a semi-solid 65 cm diameter circular shape lends itself well to a circularly polarized feed. K5OE has had excellent previous success with this circular reflector and a helix feed and wanted to apply a patch feed to this design. Having also had previous success with the K3TZ patch feed on an offset dish, it was a natural extension to apply one to this prime focus parabolic dish (4).

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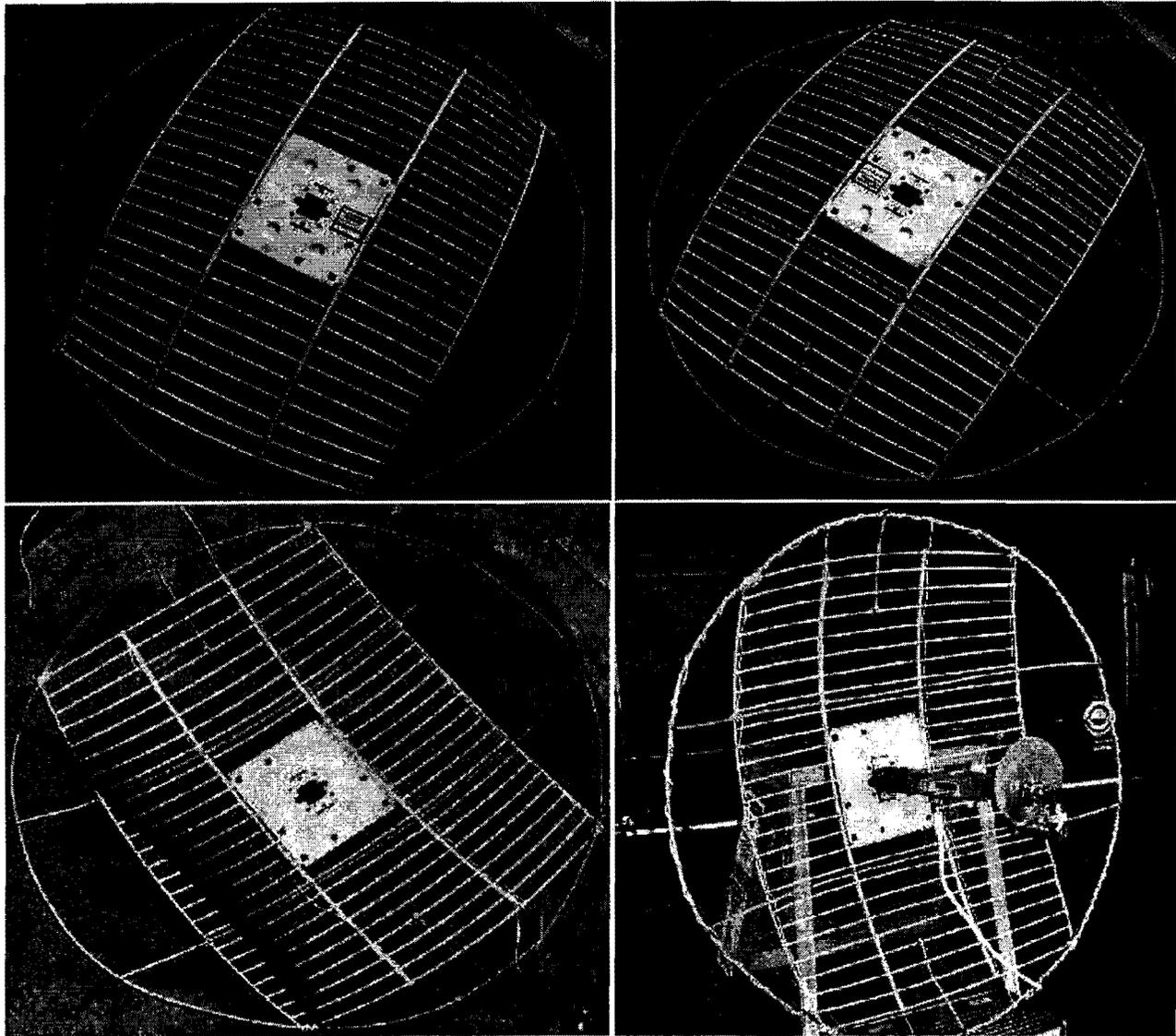
Figure 3 - Dish Construction (clockwise from top left): Perimeter Wire Loop Added; Ribs Added to Hold Perimeter Wire Loop In Place; Screen Mesh Installed; Downconverter and Patch Feed Assembled For Testing on Driveway

The stock TSI 3733 arrangement is a crafty design, with the downconverter enclosure serving as the support for an integral dipole feed. In order to retain this simplicity and efficiency, a method was devised to replace the dipole feed with the patch feed and retain the simple mechanical support of the feed by the downconverter itself. First, a special N-connector flange (available from K5GNA) was installed at the input to the 3733 in lieu of the dipole feed. To that connector, five standard N-fittings were arranged to create a support for the feed: four 90-degree and one double-female fitting. Once this was arrangement of back-to-back fittings was in place, alignment of the assembled feed + fittings + downconverter needed to be made so the feed would be at the *prime* focus of the antenna. Careful measurement of the dish diameter and depth determined the *prime focus* was located at 11 inches (275 mm) from the center of the dish. In order to mount the assembly with the feed at the prime focus, the standard TSI mounting hardware was modified (cut and re-drilled), as shown in Figure 4. Figure 5 depicts the completed feed plus fittings plus downconverter plus modified support assembly mounted in the now-circular 65 cm dish.
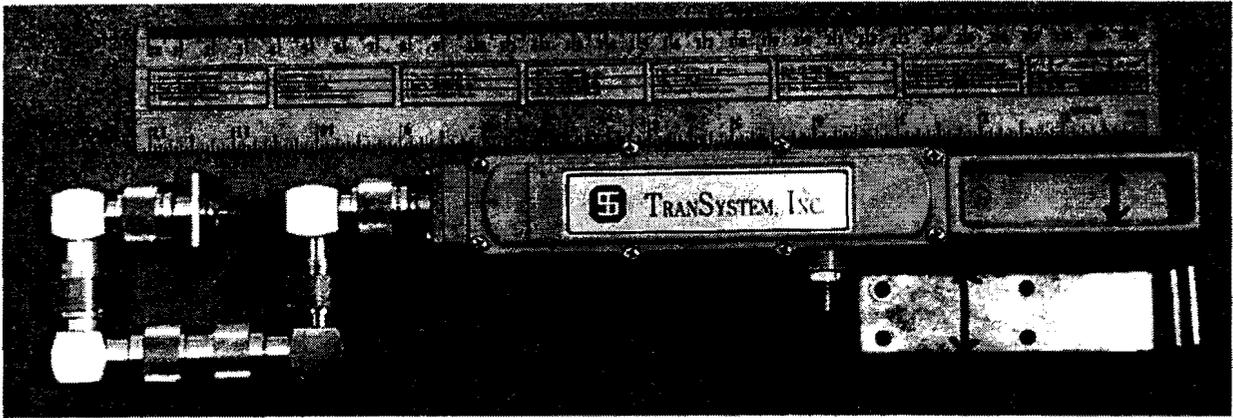
Figure 4 - TSI Mounting Hardware Modification

Figure 5 - K3TZ Patch Feed Installed on TSI 3733

On-The-Air Testing

But how would it work in the real world? Would we be able to make a non-full-duplex contact? Using non-amateur means (telephone), KK5DO and K5OE arranged a scheduled meeting frequency and time. It was a weekend morning and AO-40 was still in winter hibernation, with a high squint angle (>30 degrees) and moderate range (~35,000 km). The equipment at the P5 simulation end was an FT-100, an Arrow Antenna for the uplink, and the newly constructed 65 cm dish—all on the front deck (the satellite was in an unfavorable westerly position). KK5DO was at home using his "regular" AO-40 setup. Figure 6 shows the "P5 simulation" end of the test at K5OE: note the Arrow Antenna on the left, the compass, and the G6LVB "old tech" manual frequency aid (6). Figure 7 is the modified dish sitting on a stepladder and pointed above the neighbors' roofs.

Figure 6 - Test Setup Using FT-100 and Arrow Antenna

Figure 7 - Testing 65 cm Dish On A Stepladder Pointed West

As noted above, conditions were hardly prime, but the contact was made—first on CW and then on SSB. The receive antenna proved to be more than adequate for the situation, but we also proved what was suspected all along: a 70 cm amplifier was required for the uplink. While KK5DO was fairly easy copy on the P5 simulation end, he could barely detect K5OE's modest 15 W uplink. Of primary importance, however, was proving the concept of "split" operation using pre-arranged frequency pairs. The uplink frequency at the P5 simulation end was specified and the "listening"

frequency was specified in relation to the beacon. This is also the expected operating procedure once the equipment is in place in North Korea.

Final Setup

There was still much to do. An amplifier had to be procured. Then a second one had to be sought when an Ebay deal went sour! Hardy, DC8TS, kindly donated a 60 W mobile amplifier. Many cables, fittings, and miscellaneous hardware items had to be procured. And, finally, the whole package had to be boxed up and shipped to Beijing, where Ed would pick it up at a later date. It seems UPS does not deliver to North Korea. KK5DO and K5OE made one final "integration" check of the system, with all components in the P5 configuration, just prior to packing and shipping. In Figure 8, below, you can see the Arrow Antenna in the lower left with the dish sitting in a lawn chair. The power supply, the DC8TS amplifier, an SWR/power meter, and the FT-100 are set up and operational on AO-40 in KK5DO's driveway!
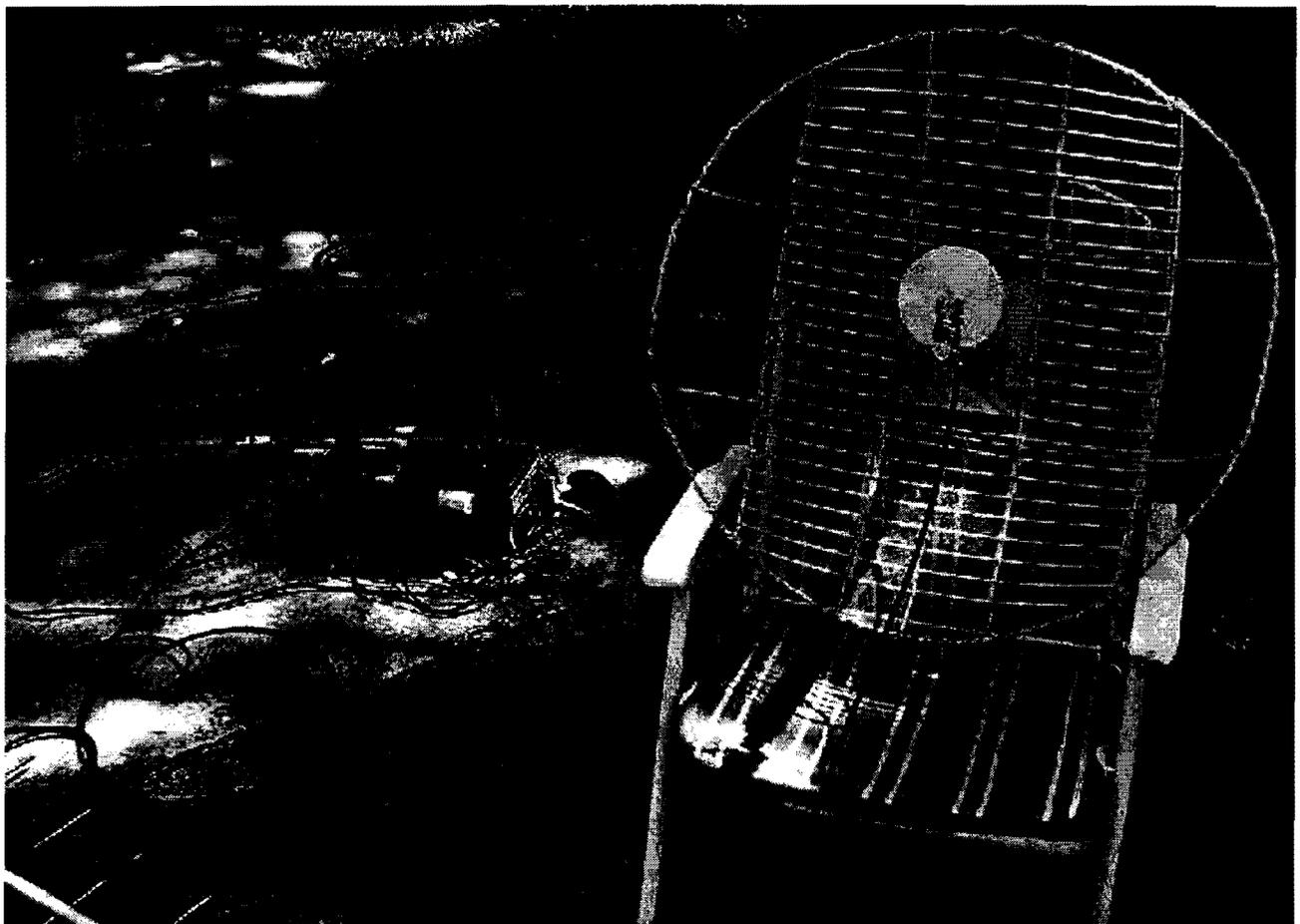

Figure 8 - The Entire Package Ready to Ship

The Rest of the Story

The rest of this story has yet to be written. The equipment has been received and is in North Korea, but Ed still has much to do. He will set up the equipment to point out the windows of his apartment. He will load and run WinOrbit software on his laptop computer (7). He has exchanged many emails with KK5DO over the many questions he has about operating satellites. Just when we were ready for a two-way contact, Ed had to leave the country for a scheduled two-week trip. Hopefully, by the time you read this Ed will have returned, been able to find the satellite beacon by manual pointing,

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and have mastered the difficult procedure of a non-full-duplex satellite contact with a piece of amateur radio equipment 62,000 km distant. With a little bit of hard work and a lot of luck, we will have a new country to count towards the seemingly impossible 100 entities required for DXCC. Good luck, Ed!
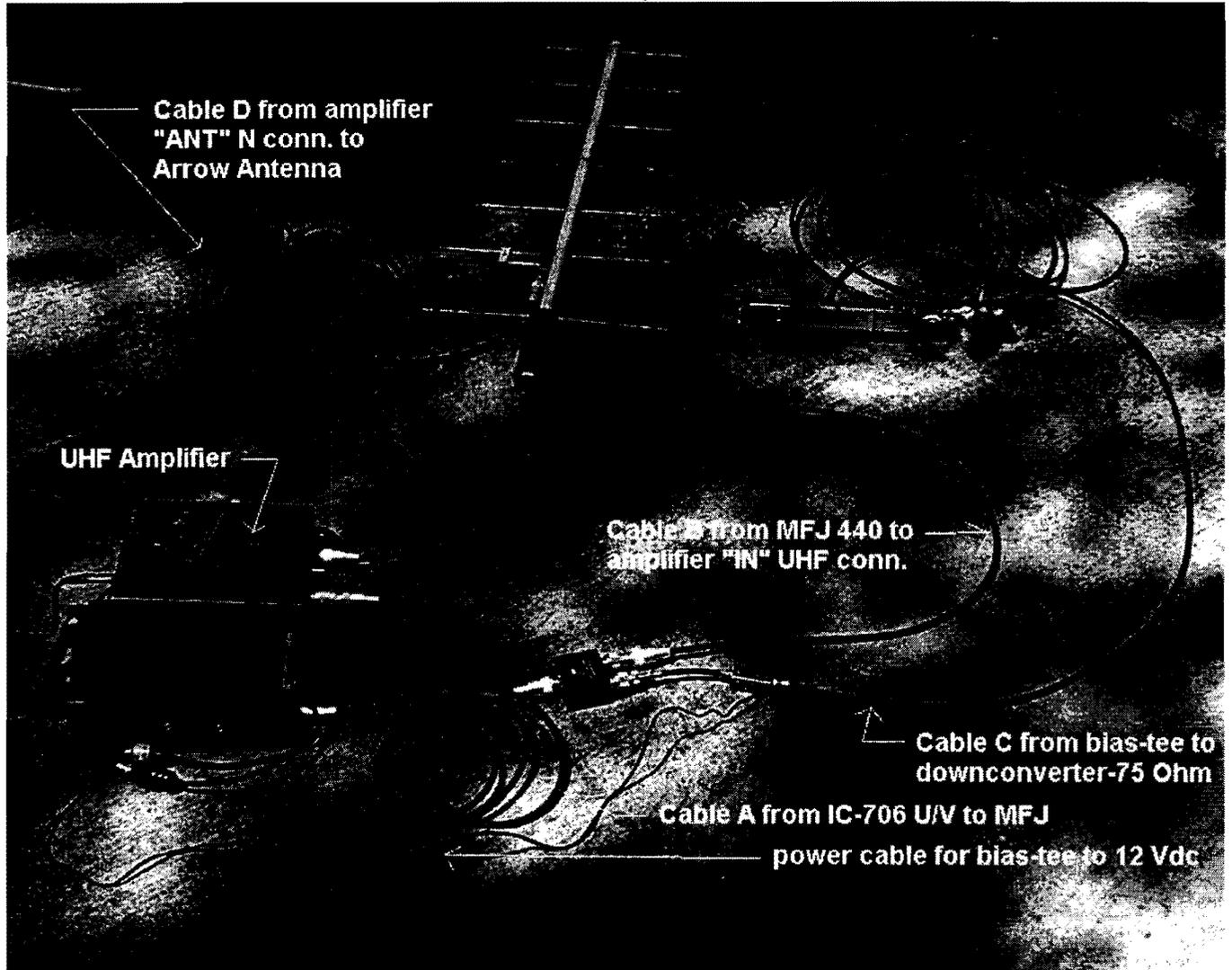

Figure 9 - The Complete P5 Configuration with FT-100 Simulating the IC-706

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A *Disposable* Antenna for Receiving AO-40 on S-Band

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Abstract: This paper presents a unique design for a 2.4 GHz receiving antenna that is so inexpensive and easy to build that it may be disposed of after use. Most of the needed materials are available in grocery stores. In spite of this, it provides performance comparable to a two-foot, parabolic dish

Introduction

Receiving the AO-40 satellite on S-band can be quite a challenge. The satellite is in a highly elliptical orbit that takes it out close to 65,000 km (~40,000 miles) at apogee and its S-band antenna is a mere 5-turn helix. In general, hearing AO-40's S-Band downlink requires a parabolic dish antenna along with a well tuned feed system to maximize the signal-to-noise ratio. This can be a daunting task, especially for a newcomer with limited satellite experience or S-band test equipment.

Given the time, effort, and complexity of putting this type of antenna system together, it might seem ridiculous to dispose of it. However, if the design allowed it to be built in less than an hour, out of ordinary household materials, with a total cost of less than $5, it could be constructed as needed and then discarded after use. This would be a disposable antenna.

It is easy to imagine applications for a disposable antenna. It would allow potential new satellite users to try-out AO-40 without making a big commitment in time or money and it could be useful to experienced operators for portable or temporary station operation. Rather than having to pack a dish antenna in one's suite-case, one could just build an antenna on-site and throw it away after operation concluded.

This paper describes the design of just such a disposable antenna for receiving AO-40 on S-band. The prototype was constructed for $3.50.

Performance

While disposability is nice, good performance is essential. The disposable antenna is designed to provide performance comparable to the types of antennas more commonly used for receiving AO-40. To provide this level of performance, the antenna needs to meet several technical performance specifications including gain, pattern, and return loss.

Since the satellite is circularly polarized, the receiving antenna may use either linear or circular polarization. The choice of polarization is a tradeoff between required gain, physical size, and complexity with the chief advantage of linear polarization being a much simpler antenna and feed system.

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The main disadvantage of using linear polarization is the 3 dB of cross-polarization loss incurred. This requires the antenna to have 3 dB more gain to maintain the same signal-to-noise ratio. However, since linearly polarized antennas do not need to be axially symmetric, they can be smaller than circularly polarized antennas with similar gain. Therefore, while less gain might be needed if circular polarization was used, the antenna would not end up being much smaller.

The other disadvantage of linear polarization is that it will incur greater signal level variance (i.e. fading) if the circularity of the antenna of the satellite is not very good. Fortunately, AO-40's 5-turn helix seems to have reasonably good circularity.

Given all the tradeoffs, linear polarization was selected with 20 dBi of gain instead of circular polarization with 17 dBi gain. This provides an overall system performance similar to the commonly used, 2-foot parabolic dish with a linear feed.

Another important aspect of the antenna design is the radiation pattern. The antenna radiation pattern must have a good front-to-back ratio and minimal side lobes. Otherwise, the antenna will see the warm earth, which will dramatically increase the received noise and reduce the signal-to-noise ratio.

Similarly, there are many other devices also using the 2.4 GHz band these days including cordless telephones and 802.11b (WiFi) wireless Ethernet equipment. The antenna should have a nice, clean pattern with a single main lobe and minimal side lobes to prevent pickup of these other signals.

Finally, the antenna needs to exhibit a reasonably low Standing Wave Ratio (SWR) in order to get the best noise performance out of the down-converter front-end. Another way of saying this is that the antenna needs a high return loss. The design goal for this antenna was a return loss of at least 20 dB which is equivalent to an SWR of around 1.2:1.

To summarize, the technical performance requirements are as follows:
- 2.4 GHz (S-band)
- 20 dBi gain
- linearly polarized
- clean radiation pattern with minimal side lobes
- return loss of 20 dB or greater

Construction Requirements

In order to make the antenna truly disposable; some additional considerations were incorporated in the design. To keep costs low, the antenna was designed with the idea of using only cardboard for the physical structure and aluminum foil for any conductive surfaces. To hold things together, packing tape, used to wrap packages for shipment through the mail, would be employed. Since cardboard and aluminum foil does not readily allow precision construction techniques, no tight tolerances may be used in the design. Similarly, to aid construction ease, any coax, connectors, or soldering was considered highly undesirable and to be minimized.

Another factor considered was the idea of using only modest tools such as scissors or box cutters to cut the cardboard and perhaps an X-acto™ knife to make finer cuts. Other tools considered reasonable included a pen, a straightedge, triangle, and a ruler or measuring tape.

A summary of the construction requirements is as follows:
- Cardboard is to be used for the physical structure
- Aluminum foil to be used for conductive surfaces
- Packing tape to be used to hold things together
- No tight tolerances
- Avoid connectors, coaxial cables, or soldering
- Only modest tools allowed for assembly

Design Overview

Clearly, any antenna that would meet the performance and construction requirements would have to be inherently broadband and highly tolerant of construction variance. Fortunately, the pyramidal horn antenna has these properties. Please see figure 1 below. Horn antennas have been used for over 100 years; the first was apparently constructed by Jagadis Chandra Bose in the 1890's and excited with a spark-gap transmitter[1]!
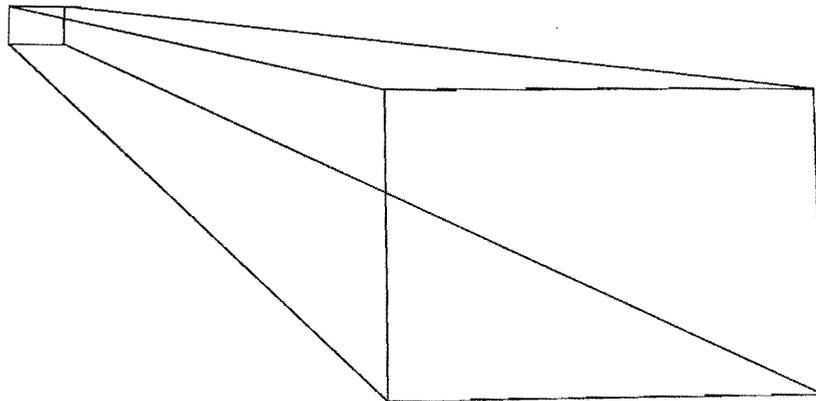

Figure 1
Basic Pyramidal Horn Shape

Horn antennas are highly predictable in their gain and are frequently used as a reference antenna for this reason. They are broadband by nature and tolerant of mechanical deviations in their structure. Horns can provide excellent front-to-back ratios and, a very

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[1] D. T. Emerson, *The Work of Jagadis Chandra Bose: 100 Years of mm-Wave Research.* IEEE Transactions on Microwave Theory and Techniques, December 1997, Vol. 45, No. 12, pp.2267-2273

clean radiation pattern with minimal side-lobes. Horns have been well characterized in the technical literature and a wealth of design information is readily available.

A pyramidal horn antenna with 20 dBi of gain is about the same size as a 2-foot parabolic dish but unlike a dish, does not require tight tolerances in its construction. For all these reasons, the disposable antenna is based on the pyramidal horn shape and the basic design information was taken right out of the pages of Kraus.[2] The horn aperture is about 3 λ high by 4 λ wide and 5 λ deep.

A unique feature of the disposable antenna design is the elimination of the waveguide feed usually used with a horn antenna. Instead, the horn is directly excited with a 1/4 λ probe in the flared part of the horn itself. This eliminates the need for difficult to build angles as well as any couplings or waveguide flanges.

The main disadvantage of this technique is in the more complex, up-front design work. Inside the waveguide, the wavelength depends on the frequency and the width of the guide. The probe to excite the waveguide is needed one quarter of a wavelength from the closed end. However, in the flared part of the horn, the wavelength is not a constant but instead varies as a function of the distance from the closed end of the horn. This type of construction is not commonly used in commercial applications and hence design information is not generally available in textbooks.

For the disposable antenna, the problem of the probe location was solved by developing an equation that described the phase as a function of the distance from the closed end of the horn and integrating until 90 degrees of phase was accumulated. The resulting equation is then solved for the probe distance. For those interested, the disposable antenna excites the TE_{10} mode and the equation to solve the probe location is shown below:

$$\frac{\lambda}{4} = \int_{x=0}^{D} \sqrt{1 - \frac{\lambda^2}{4 (wx + a)^2}} \, dx$$

Where:
    λ = The free space wavelength
    x = The perpendicular distance from the closed end (i.e. depth coordinate)
    w = The width factor of the flair (i.e. Δ width / Δ depth)
    a = The width of the closed end
    D = The required probe distance from the closed end

This equation might be hard to solve analytically, but fortunately is easy to solve numerically using Microsoft Excel[TM]. It also is fortunate that this dimension is not very

[2] John D. Kraus, *Antennas*. McGraw-Hill, Inc. 1988.

critical and so is consistent with the cardboard construction requirements. The use of direct excitation significantly simplifies the construction of the antenna.

Another simplification in the design is to eliminate the need for any coaxial cables or connectors. Instead, the down-converter is mounted directly to the horn via it's own female, N-connector. The connector is fastened with a 5/8"-24 nut. A probe made of a short piece of 14-gauge wire is inserted into the N-connector to provide the coaxial to waveguide coupling to the horn.

Materials

The structure of the disposable antenna is made of cardboard. A very inexpensive source of cardboard is old shipping cartons available from a grocery store. These are generally free for the asking. The large size standard carton is around 16" x 22" x 22" of 1/8" thick cardboard though, the exact size is not critical. Two cartons are needed. One is cut up and used to make the horn side panels and the other is used to support the horn structure.

The horn panels are covered with aluminum foil, which is held in place with packing tape. It is suggested that 18" wide aluminum foil be used to make construction easier. Similarly, 2" wide packing tape is suggested.

The most exotic component required is a 5/8"-24 threads-per-inch nut. This is the size required to screw onto the threads of a female N-connector. This nut is supplied with single-hole, chassis, and bulkhead coaxial (N and UHF) connectors and is also widely used for other types of circular connectors. A modest junk box will often include several of these nuts but they are also readily available from coaxial connector suppliers for about $.50 each.

The only other component required is a short length of solid, bare, 14 gauge (AWG) copper wire for the coaxial to waveguide coupling probe. This is to be cut as carefully as possible to 1-5/8" inches long and will be inserted into the female N-connector of the down-converter. Note that the diameter of 14-gauge wire is within the diameter tolerance for a proper N-connector center pin and so will fit snugly yet not deform or damage the female N-connector on the down-converter.

The complete list of materials is as follows:
- (Quantity - 2) Cardboard shipping carton, (around 16" x 22" x 22")
- Roll of 18" wide aluminum foil
- Roll of 2" wide, clear packing tape
- 5/8"- 24 nut to fasten N-connector
- 1-5/8" length, solid, bare 14 gauge (AWG) copper wire

Construction

To start construction, carefully unfold one of the cardboard cartons. You will need all of the sides plus the top and/or bottom flap of each side to make the horn panels. Use the 22" wide sides to make the top and bottom horn panels and the 16" wide sides to make the two horn side panels. Please see figures 2 and 3 for the detailed dimensions of the horn panels. The top and bottom horn panels are the same except for a 5/8" hole in the top panel that will be used to mount the down-converter.
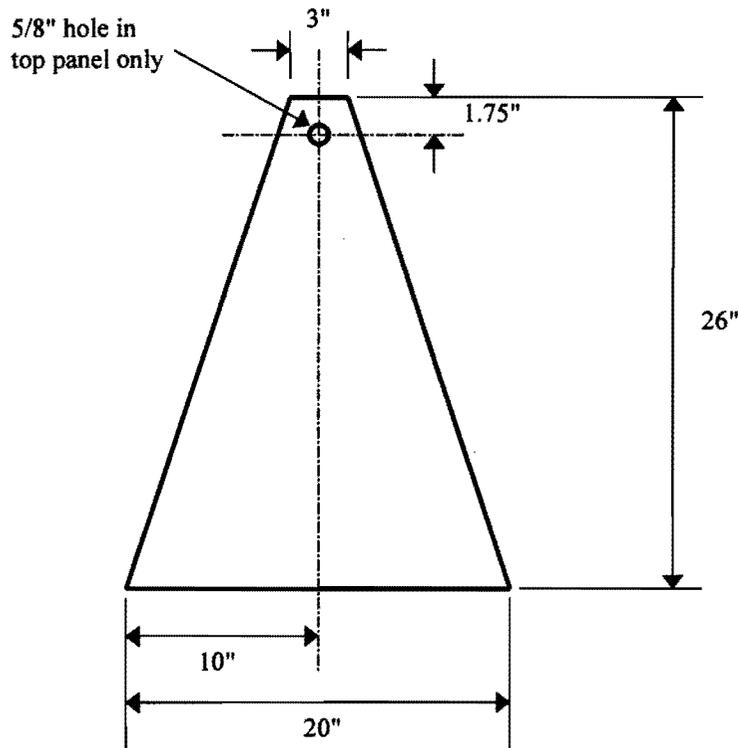
**Figure 2
Horn Top and
Bottom Panels**

Draw the horn panels on the cardboard carton sides as carefully as possible and then cut out the horn panels with either a box cutter or scissors. Be careful not to mangle the cardboard! After cutting out the horn panels, it may be helpful to apply some tape to strengthen the panels.

Next, apply the aluminum foil to one side of each horn panel, roll it over the edges of the panel, and tape it snuggly on the back side to hold it in place. The foil needs to cover all of the edges of the cardboard panels Do not allow the tape to run over the edge of the panels. The foil on the edges will be used to make electrical contact with the panels.

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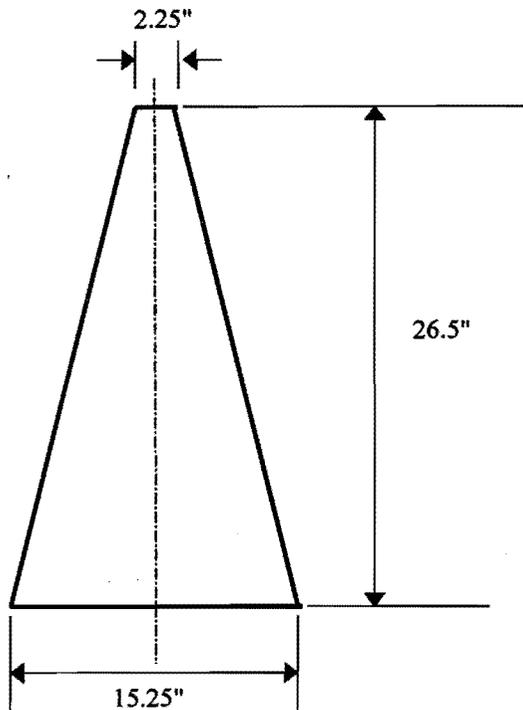
**Figure 3
Horn Side
Panels**

The horn side panels are only 15.25" wide so a single piece of 18" wide aluminum foil can be run lengthwise to cover the entire panel. The top and bottom panels are too wide for this so instead run the foil across the panel (i.e. along the front 20" edge) and use a second piece of foil to cover the back of the panel. Leave an inch or so of overlap between the pieces. You do not need to tape them together. Carefully cut and push back the foil through the 5/8" hole in the top panel.

Once you have created the panels, they need to be taped together. The easiest way to do this is the place all four panels on a flat surface **foil side down** and aligns the long edges together. Make sure to put the side panels in-between the top and bottom panels. This will then look like an unfolded, flat horn. The long edges are all about 27.3" so they should all line up. You will be taping the three long sides that are touching.

Separate the edges from each other by 1 cardboard thickness (~1/8") using a scrap piece of cardboard and then tape the backs (**not the foil side**) of the panels together. This is important; the long panel edges need to be taped 1 cardboard thickness from each other in order to make good electrical contact when the horn is folded together.

After the panels are taped together, but still flat, carefully pick up the panels, form the pyramid shape, and tape the remaining edge tightly. When you form the pyramid, the cardboard on the edges will slightly crush which will hold the aluminum foil covered edges together making good electrical contact. After taping the fourth edge, hold the pyramid up to a light to see if there are any gaps between the edges. There will probably be a few. The design can tolerate 1/4" to 1/2" gaps without problems. Carefully tape the

larger gaps to pull the edges together better. If you end up with any really large gaps, patch them with foil and tape.

The pyramid will not hold its shape at this point so set it aside for now and get the remaining cardboard carton. This carton will be used to hold the pyramid, providing both structure and protection. We will be taping the mouth of the pyramid to the open end of the cardboard carton. The top and bottom of the pyramid are about 15.5" apart at the mouth and will fit nicely into the 16" wide opening on the carton. However, the pyramid will be about 25" deep from front to back, which is too big for the carton. We need to cut a hole in the bottom of the carton to allow the back of the pyramid to fit through. The hole should be centered in the bottom of the carton and will need to be around 5" wide by 3.75" high. You will need to trim this hole to fit the pyramid.

Once you have the hole completed, center the pyramid in the carton. Next, align the front of the pyramid with the open end of the carton so it is flush and tape the top and bottom edges of the pyramid to the carton opening. There should be about 1" on each side between the pyramid sides and the carton sides. Apply some more tape to secure the back part of the horn to the hole in the back of the carton. Please see the photo of the completed horn in figure 4 but note that the back end will still be open at this point.
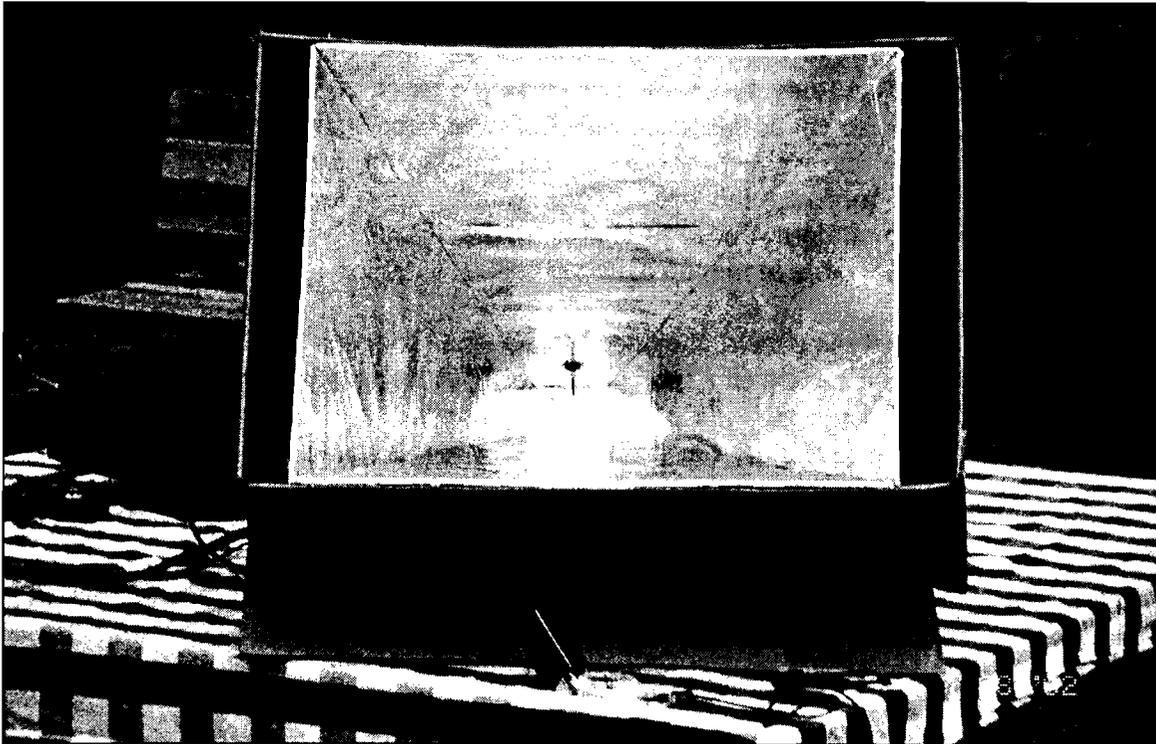

Figure 4
Front View of Horn

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Now it is time to mount the down-converter. Cut three or four 2" x 2" pieces of cardboard from the remaining scrap and cut a 5/8" hole in each piece. These will be used to make a spacer for the down-converter. Slip the cardboard spacers over the N-connector on the down-converter. Being careful not to rip the aluminum foil, push the end of the N-connector through the 5/8" hole in the top panel at the back end of the horn and secure with the 5/8"-24 nut. You will need to compress the cardboard spacers a little to do this. The top of the connector should be just about flush with the top of the nut when it is secured. The idea is to use the resiliency of the cardboard spacers to hold the down-converter nice and tight in the hole but you do not want the connector to protrude very much into the horn. The down-converter will still have a fair amount of play in the hole.

When the converter is mounted, take the 1-5/8" piece of 14 gauge wire and gently push it into the center hole of the N-connector until it won't go in any further. When seated properly, the wire probe should protrude around 1-1/4" past the edge of the N-connector into the horn. Hold the down-converter so that the probe is about parallel with the back plane of the horn and use tape to hold the down-converter in place. Please see the photo in figure 5. Finally, use a piece of aluminum foil to cover the back end of the horn using tape to hold it taught. Congratulations, your disposable antenna is now complete!
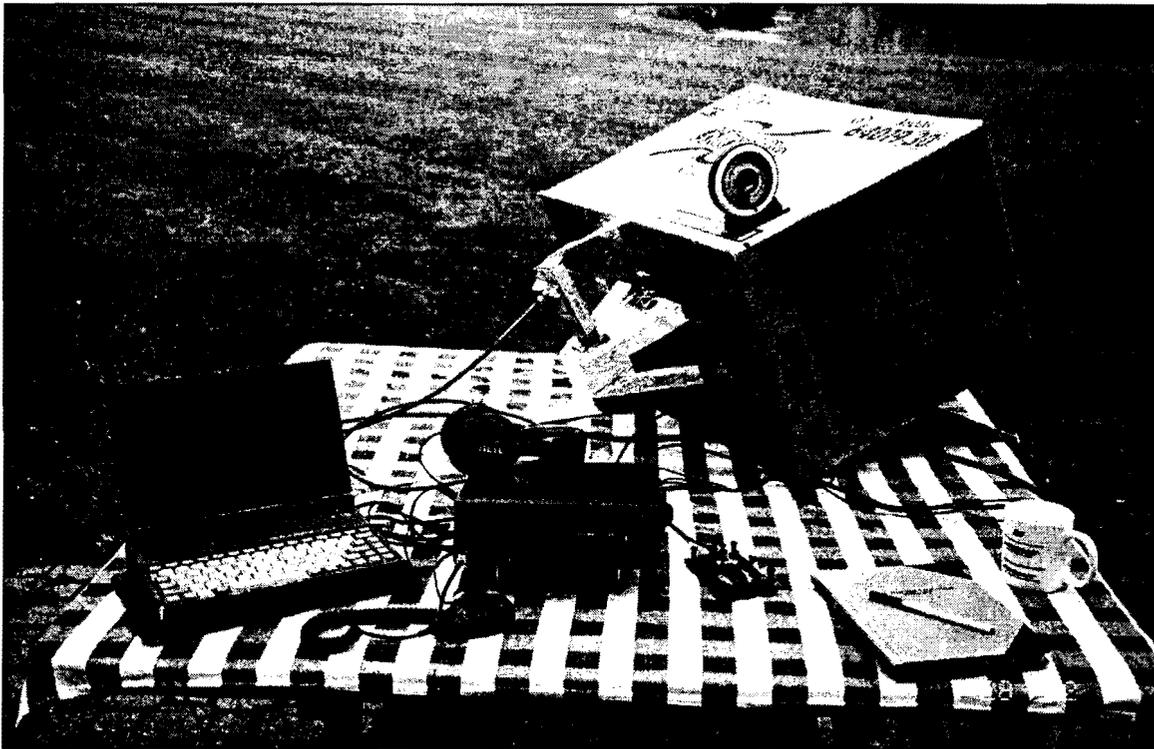

Figure 5
Back View of Horn with Down-converter

Testing

The return loss design goal of greater than 20 dB was verified by temporarily substituting a bulkhead, N-connector for the down-converter. The return loss was measured at greater than 23 dB, which is the limit of the author's S-band test equipment. A Narda *Microline*™ termination, used as a reference, measured the same as the disposable antenna. This testing was done only to verify the design; individual antennas do not need to have their return loss tested this way.

The easiest way to test a new disposable antenna is to point the antenna at the satellite and tune around for the beacon. A certain amount of trial and error will be needed to find the satellite beacon the first time due to frequency and pointing errors. With a little experience however, this is a snap. The satellite beacon is easy to hear and will be a very strong signal.

Antenna Pointing

The antenna has a beam-width of about 15 degrees in both azimuth and elevation so pointing it is not that critical. For elevation pointing, it may be helpful to tape some additional pieces of scrap cardboard to tilt up the outer carton as can be seen in the photo in figure 5. You can also just prop up the carton with a heavy object.

A protractor will be helpful for setting the elevation angle. Most good compasses have a protractor function that you can use to measure the elevation angle. The azimuth can be set by pointing the antenna using a compass. It is helpful to know the magnetic variation in your area. This is the difference between where the compass points and true north. This difference can often be greater than the antenna beam-width.

You will need to know the position of the satellite in order to point the antenna. There are many satellite tracking programs available including some free ones. AMSAT's web site; www.amsat.org is a good source for information on satellites and tracking.

On-the-Air

Does this antenna really work? Yes! The author has used this antenna on several occasions to receive AO-40. The complete station setup uses an AIDC-3731AA down-converter running at an intermediate frequency of 123 MHz into a Yaesu FT-847. A laptop computer running *Instant*Track and *Instant*Tune software is used to track the satellite and auto-tune the FT-847.[3]

Once you have managed to find the beacon, you can decode the satellite telemetry. A convenient way to do this is using the *ao40rcv* program available for free download at http://www.qsl.net/ae4jy/ao40rcv.htm. This program uses the sound card in the PC to demodulate the signal and decode the telemetry. This was tested with the disposable receiving antenna and worked great.

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[3] *Instant*Track and *Instant*Tune are available from AMSAT at www.amsat.org

The author also constructed an UHF (435 MHz) uplink antenna out of leftover cardboard and aluminum foil. Details of this antenna are beyond the scope of this article but it is a dipole-fed, corner reflector calculated to have a gain of about 14 dBi (linear.) With the FT-847 set to for it's maximum of 50 watts, this yields over 600 watts of effective radiated power (EIRP) which provides a solid Single-Sideband (SSB) uplink signal even when the satellite is at apogee.

The uplink antenna does not require elevation control because its elevation beam-width is wide enough that it can be fixed with a pair of cardboard "legs." The complete set-up can be seen in the photo in figure 6.

Figure 6
Operating on AO-40

On the table from the left, are a laptop computer, a Yaesu FT-847, and the disposable receiving antenna. The down-converter can be seen sticking up, out of the back end of the antenna and is connected to the FT-847 with a short piece of RG-6 coaxial cable. On the patio to the right of the table is the uplink antenna. It is connected to the FT-847 with a section of 9913-type cable.

With this simple arrangement, using the antennas made out of cardboard boxes, several dozen 2-way SSB, and CW contacts were made through AO-40 over a couple satellite

passes. While most contacts were with USA stations, some DX contacts were also made. Examples of a few DX contacts from the operating logs are shown below in figure 7.

Date	Call	Mode	RST Sent	RST Rcvd	Name/QTH
7/20/02	5K0Z	SSB	5/4	5/5	Ingolf, Providence Island
7/25/02	F1ORL	SSB	5/5	5/5	Pascal, France
7/25/02	7X0DX	CW	579	579	Mirek, Algeria
7/25/02	I8CVS	SSB	5/7	5/7	Dom, Italy
8/2/02	ON5NY	CW	559	569	Walt, Belgium
8/2/02	G0MRF	SSB	4/4	5/4	David, England
8/2/02	VE6BGT	SSB	5/5	5/3	Kip, Canada
8/6/02	LZ1DP	SSB	5/5	5/6	Chris, Bulgaria

Figure 7
Example DX Contacts made on AO-40

Summary

This article has presented a design for a *disposable* antenna that can receive AO-40 on the S-band (2.4 GHz) downlink. It can be easily assembled in less than one hour and is made from cardboard, aluminum foil, and packing tape. No soldering, coaxial cable, or connectors are required. The prototype was constructed at a total cost of $3.50 from materials found at the local grocery store.

In spite of it's simplicity and low-cost, the *disposable* antenna has 20 dBi of gain and a clean radiation pattern providing a signal-to-noise ratio comparable to that obtained from the more commonly used 2-foot, parabolic dish. This high performance level allows good reception of the AO-40 satellite, even at apogee.

There are many applications for the *disposable* antenna, including portable and temporary station operation, and it can provide an easy, low-cost way for new operators to get started on AO-40.

Dual-Band Dish Feeds for 13/23 cm

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Many myths abound regarding "large" parabolic dish antennas. The definition of "large" is subjective, of course, but dishes greater than 1 m in diameter are generally considered too large for most amateur rotator systems, and are commonly avoided. Another typical constraint is the assumption a separate dish is required for each band of interest. This paper challenges these notions, provides some current relevant examples, and presents an easy-to-build large dish for AO-40 that is within the means of most satellite experimenters and operators—and their rotators.
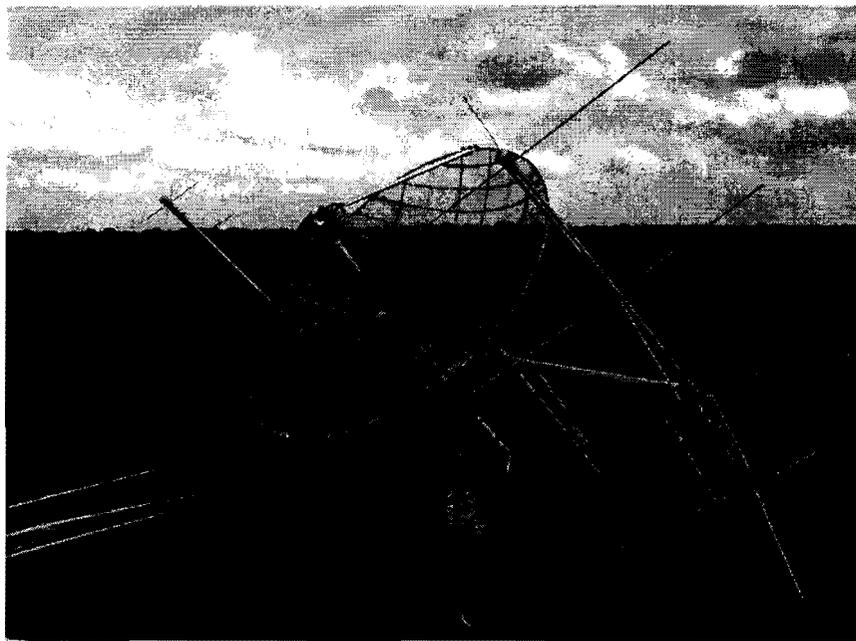
Figure 1 - The 1.2 m Dish Installed Between U and V Antennas

AO-40 Experience:

If one pays attention, it does not take long to notice something on the AO-40 transponder: L-band uplink signals seem to have some distinct benefits over the more populous U-band uplinks. The L-band uplinks seem to suffer less from the effects of both QSB and AGC action The superiority of L-band uplinks is especially notable under pile-up conditions and contest conditions. The recent ARRL/AMSAT Field Day experience certainly highlighted the dominance of L-band uplinks under crowded conditions. Perhaps these distinctions will go away when the L-band uplink becomes more popular, but it certainly has advantages today.

It would only be fair to also mention a couple other general observations: it appears more uplink power, in terms of effective radiated power (ERP), is required for L-band when compared to U-band, and the L-band antenna on AO-40 seems to fall off in gain at high squint angles noticeably faster than the 70 cm antenna. The author's unscientific observations indicate, under good conditions and bad conditions alike, double the ERP is required for equivalent signals on L-band. For example, ignoring coax losses and other inefficiencies, a 50 Watt UHF station with a typical 13 dBi antenna, will have a 1,000 Watt ERP uplink. Thus, 20 Watts of L-band power and a 20 dBi antenna are recommended by the author for comparable good signals (2,000 Watts ERP). With smaller antennas, 40 and 80 Watt amplifiers are not uncommon (1). Clearly, L-band is not necessarily the "easy" way to go for AO-40 uplink. The benefits and detractors should be carefully weighed by any operator considering moving from U-band uplink to L-band uplink.

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Some AO-40 operators use converted TVRO dishes, typically in the 3 m diameter size range, for the S-band downlink as well as the U-band uplink (2). If these truly large dishes are employed successfully for the U-band uplink, might not a smaller dish work well for L-band uplink in combination with S-band downlink? The author obtained a surplus 1.2 m UHF TV dish of ancient vintage, defining the starting point for this project/experiment. This dish was constructed in two pieces of galvanized wire grid with about 3" (75 mm) separation of the "grid." It is quite light in weight considering its relatively "large" size. As with all good ideas, there need be both a theoretical basis and a practical application of the theory, so the project was based on the available dish and not any particular magic in the 1.2 m size.

The Math:
Is this dish big enough? The prime focus parabolic antenna gain equation is expressed as (3):

$$G = 10 * Log_{10}[\eta(4\pi/\lambda^2)*A], \text{ where } \eta=\text{efficiency}, \lambda=\text{wavelength}, A=\text{aperture of the dish}$$

$$G = 10 * Log_{10}[0.50(4\pi/86.72)*(3.14*576)], \text{ where } A= \pi r^2$$
$$G = 10 * Log_{10}[0.0724*1807]$$
$$G = 21.2 \text{ dBi at 1269 MHz}$$

$$G = 10 * Log_{10}[0.50(4\pi/24.5)*(3.14*576)], \text{ where } A= \pi r^2$$
$$G = 10 * Log_{10}[0.2564*1807]$$
$$G = 26.6 \text{ dBi at 2401.5 MHz}$$

From these calculations, a nominal 1.2 m dish will yield 21 dBi on L-band and almost 27 dBi on S-band with an assumed 50 percent efficiency. 20 dBi is a power gain of 100, making a very nice improvement over the author's UHF uplink potential (30 W into a 13 dBic antenna).

Where does the feed get mounted? The *focus* is where the parabolic shape of the dish concentrates the reflected signal. The *prime focus* of a paraboloid is determined by the following equation:

$$f = D^2 / 16d, \text{ where D=diameter of the dish and d=depth of the dish}$$

For this antenna, the author assembled the two main pieces and placed the antenna flat on the garage floor to measure the depth, and thus determined (4):

$$f = 48^2 / 16*7.25 \text{ (inches)}$$
$$f = 2304/116$$
$$f \approx 19.8 \text{ in. (50.5 cm)}$$

1.2 m Dish Construction:
First, the dish was cleaned and bolted together. Then aluminum window screen was secured to the front of the dish by weaving small-gauge wire between the ribs. Still, the dish remained "wobbly," so a flat galvanized steel plate 12" square (300 mm) was added to the back of the dish to provide some much needed rigidity. The plate was secured to the wire ribs using 1/8" galvanized u-bolts of the type used for clamping ropes. This plate also served as a convenient mounting spot for a pair of U-bolt mast clamps for attaching the boom. The ribs of the dish were so far apart the aluminum screen had a tendency to pucker in many places, so hot-glue was used to adhere the screen to all the ribs. This worked exceedingly well for such a simple solution. Not being sure of the UV deterioration effects on the glue, the whole dish surface was spray painted with enamel.
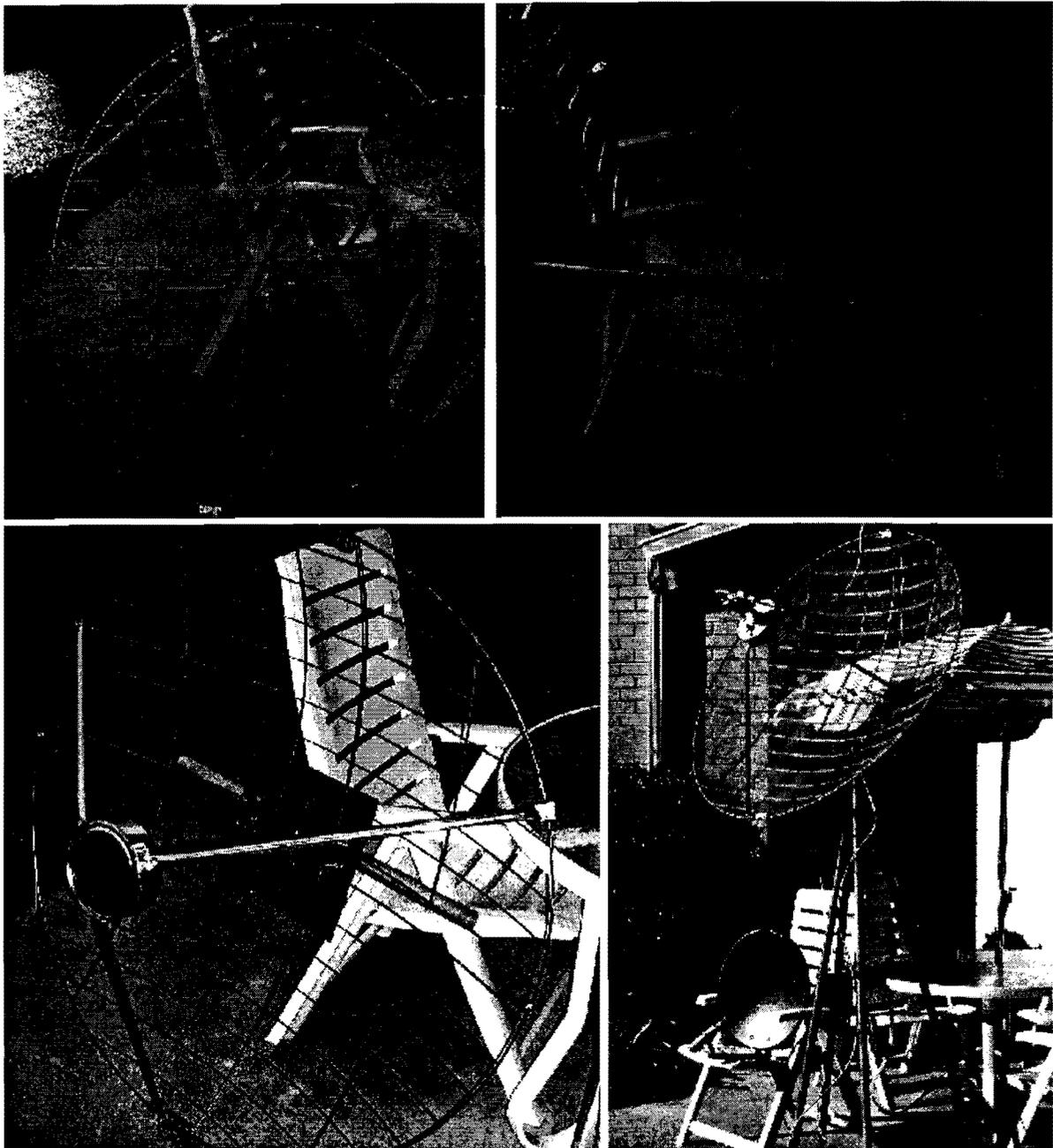
Figure 2 - The Dish (clockwise from top left) aluminum mesh installation, pipe clamps and center support, feed and supports installed, and testing on patio using an 18" DSS dish for S-band signal comparison.

Next came attachment of the feed. Three support arms were fabricated from thin gauge aluminum tubing. The ends were merely pounded flat and drilled to provide surface area for bolts, washers, and nuts. To ensure the feed was in the proper location, a support jig was fashioned from some scrap lumber to position the feed at the proper location while the aluminum tubing was cut, hammered, drilled, and bolted in place.

Helix Feed Design:
The author considered several feed designs, including patch designs such as W0LMD's round patches or K3TZ's square patches, and a parasitic dipole+reflector feed, such as WC9C's (5, 6, 7). The arrangement of coaxial helices was demonstrated by ON6UG at the 1989 AMSAT-UK Colloquium and various versions have subsequently appeared over the years (8). Ultimately, the concentric helix design was chosen, in great part due to the flexibility of this design to add further,

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higher frequencies in the future: see the G3WDG website for pictures of a tri-band feed incorporating a 24 GHz feed horn coaxially within 13/23 cm helices (9).

While G3WDG utilized the popular G3RUH helix feed method, the author chose to stay with the simple design developed on earlier successful antennas (10, 11). The dimensions for these helices are shown below in Table 1 and the completed helices are shown in Figure 3 as installed in a 6" (15 cm) diameter "cup."

Table 1 - Helix Parameters

	23 cm	13 cm
Design Frequency	1269.300	2401.350
Diameter	3.12" (79 mm)	1.65" (42 mm)
Pitch (degrees)	12.5	12.5
Spacing (1st turn)	1.4" (35 mm)	0.75" (19 mm)
Spacing	2.2" (56 mm)	1.18" (29 mm)

Figure 3 - Concentric 13 cm And 23 cm Helices In The Paint Can "Cup"

The cup is made from a virgin paint can, cut down to about 1-1/2" (40 cm) deep. The *phase center* of a helix is near the end of the first turn, thus the optimum location for each of the two helices cannot both be coincident to the *focus* of the dish (12). Since the antenna has much more S-band gain than L-band gain, the feed was arranged so the *phase center* of the L-band helix was at the *focus* of the antenna. This then set the rear of the feed at about 21.2" (54 cm) from the dish. Figure 3 depicts the feed after soldering of the helices onto the 180-degree-separated N-connectors. Note the first ¼ turn of each helix has the insulation left on and is placed flat against the back of the feed cup.

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Electronics:

The biggest technical challenge to this project was finding or building a suitable filter to block the energy from 1269 MHz from getting into the S-band preamp and either de-sensing the preamp or possibly even destroying it. Since both helix feeds are near the focus of this dish and 2401 is less than 150 MHz from the first harmonic of 1269 MHz, this is not an insignificant concern. I spoke to several people on AO-40 who had built their own filters, but after investigating the various options, I opted to purchase G3WDG's circuit board etched filter made especially for this service (13). After discussing the application with G3WDG, he recommended the dual notch filter, rated at 100 dB rejection of the offending 23 cm signal. This filter is packaged in the same tin metal enclosure as the DB6NT 13 cm preamp, and I found 1-1/4" PVC a suitable weather enclosure for the pair (14).

Figure 4 - G3WDG Filter And DB6NT Preamp Go Inside 1-1/4" PVC Pipe

On the Air:

This antenna, after sitting in my garage for several months, was installed on the roof for a special event: a proposed contact with N1JEZ for his first attempt at a QSO using the K-band downlink. He was successful in hearing my L-band uplink on the K-band downlink and I could also copy his SSB signals on S-band (15). I was his first K-band contact and he was my first L-band contact— we were both elated. Subsequent testing indicates the notch filter performs perfectly, without a hint of de-sense from the L-band uplink running about 20 W at the antenna. In subsequent testing I have inserted and then removed the filter, carefully watching the S-meter readings. There is no perceptible loss of S-band signal with the G3WDG filter in line. The L-band uplink, however, was unimpressive. In side-by-side tests, my U-band uplink was better. Something was wrong, but I lacked test equipment to really analyze the feed or the antenna in any meaningful way.

Dual-Band Patch Feed:

While I waited for an L-band power/SWR meter to arrive (to troubleshoot the L-band helix feed), I decided to see if I could apply the K3TZ patch I had so successfully used in S-band service to a dual-feed design (16). Using a pair of patches has an intriguing potential benefit: higher efficiency and better pattern from near-alignment of the phase centers of both patches to the focus of the dish. A dual-patch design, using the 23 cm patch as the reflector for the 13 cm patch, only has a focus offset error of 3 mm instead of the 16 mm error in the concentric helices. Scaling the 2401 MHz design to 1269 MHz was a simple matter and I quickly cobbled my idea together using some sheet aluminum and a 6" double-sided copper PC board. The 6" reflector is slightly smaller than an optimum reflector for this 23 cm patch, but I did not want to increase the *feed blockage* of the antenna with a larger reflector. Simulations show very little degradation of the patch antenna with this reduced-size reflector. This first effort is shown below as the PC board was cut to 6" round, then the N-connectors were added, and then finally the aluminum patches were added.

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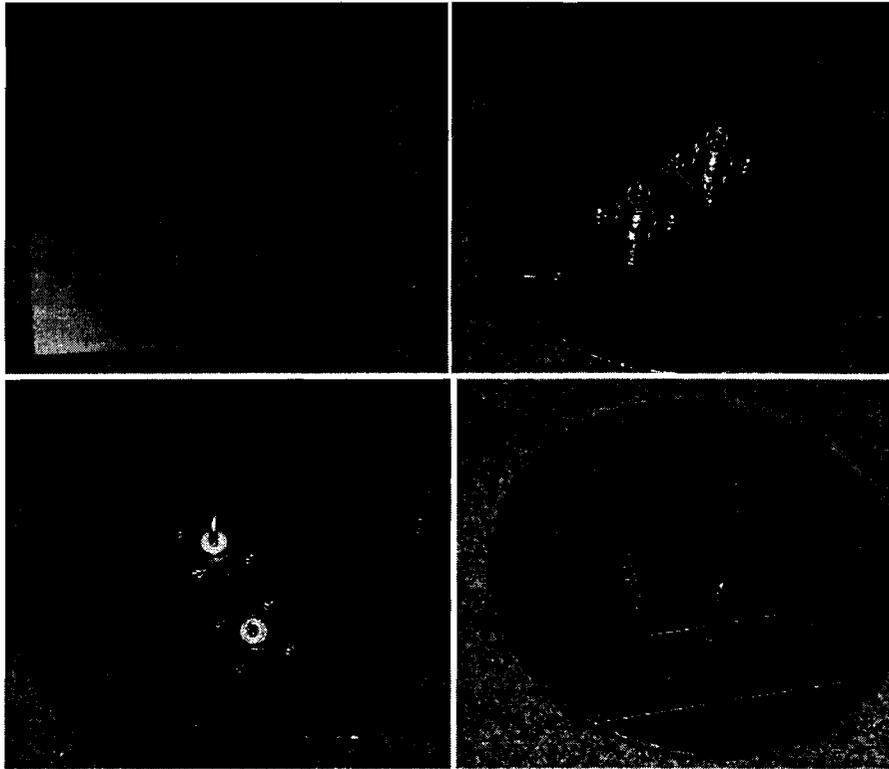
Figure 5 - Dual Patch Feed Construction

This patch feed bench tested as superior to the dual-helix feed on both frequencies: a weak signal source (10 MHz crystal oscillator at 2400 MHz) was used for the S-band signal test and an SWR meter employed to test the match on the L-band antennas (17). I also learned an important lesson in this effort: aluminum is difficult to solder, causing the TFE insulation in the N-connectors to melt! Figure 6 depicts the "improved" model using copper sheet stock for the patches and fitted to the 5' (1.5 m) solid dish used for the AMSAT Field Day competition.
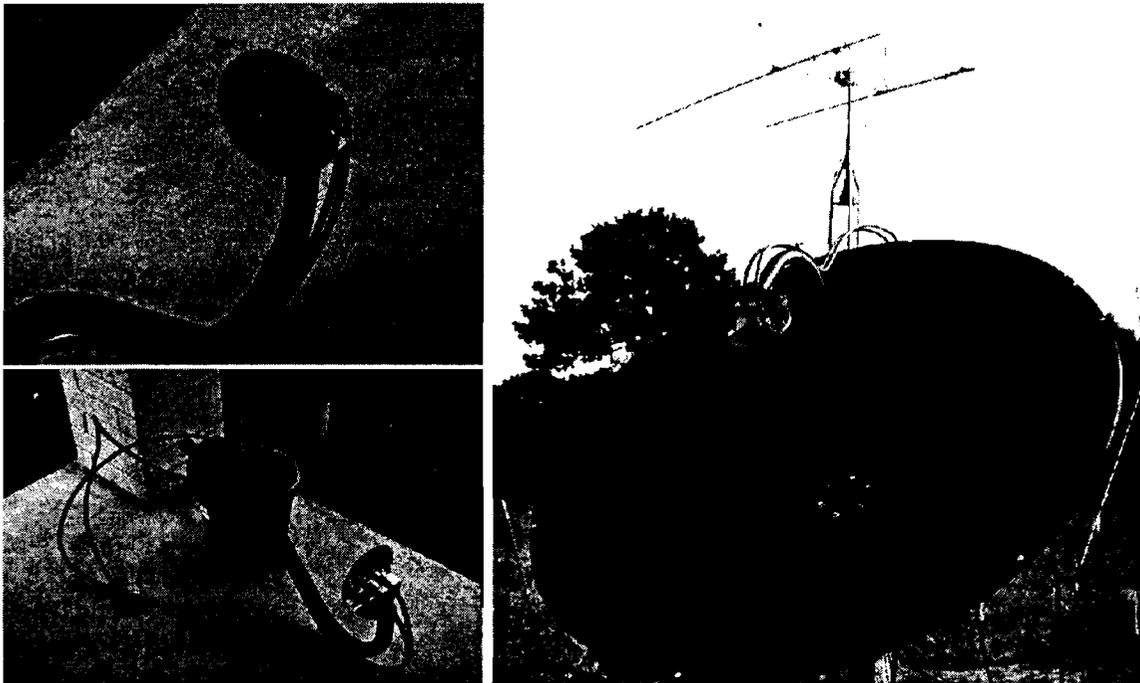
Figure 6 - Dual Patch Feed Mounted on the 5' Field Day Antenna's "Button Hook"

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The Field Day experience was confounding. This antenna performed extremely well on L-band uplink, providing a solid, easily copied signal. The receive signal, however, left much to be desired--considering the significant gain figures anticipated from this dish. The S-band signal was no better than my 2' dish at home. Something was amiss, but again I was stuck with a built antenna and no test gear. Two days after Field Day I drove out to the AG5RS "Katy, Texas, RF laboratory" with a collection of feeds and swept them all. I learned the patch feed was indeed superior to the helix in return-loss response, but serious questions about the mechanical design of the dual L/S-band patch feed emerged from this investigation.
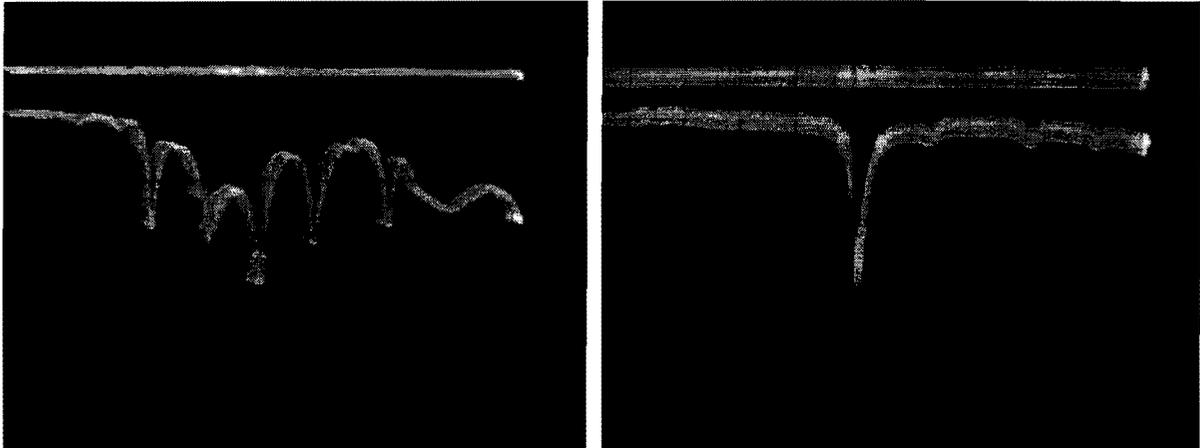
Figure 7 - L-Band Helix Feed (left) Compared to Patch (right) at 10 dB/grad

Figure 7 depicts the L-band dual helix on the left and the L-band dual patch on the right. Although the patch was resonant a little high at 1295 MHz (1.7:1 SWR at 1269 MHz measured on Field Day), its response was substantially better than the helix and it's real-world performance was quite rewarding. This was clearly noted on Field Day, as the K5OE signal was very strong at apogee with 20 W at the feed. I suspect the helix feed has interaction between the L and S elements.
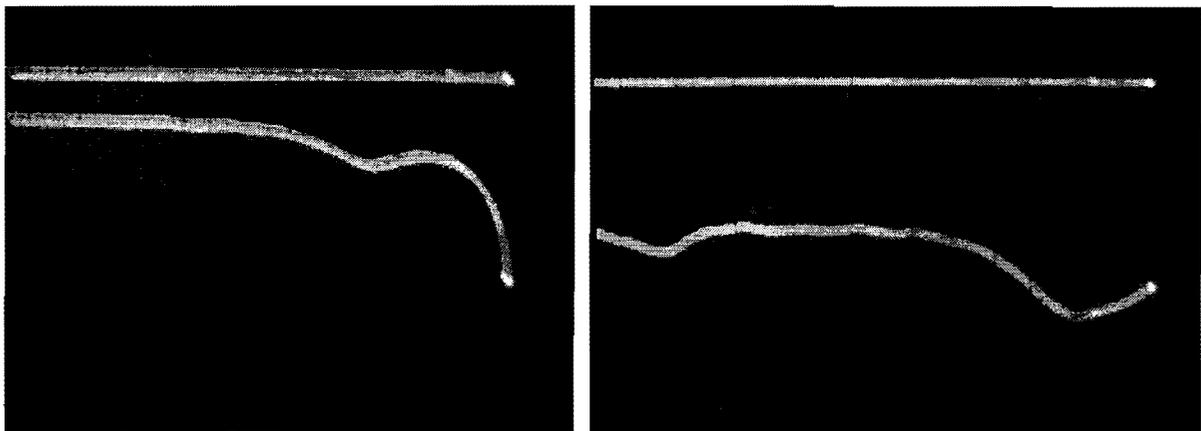

Figure 8 - Lone S-Band Patch (10 dB per grad.) Compared to Dual Patch (at 5 dB per grad.)

Figure 8 depicts a lone S-band patch on the left (2400 MHz is the far right edge of the sweep) with a clearly impressive response. This particular patch feed works exceedingly well on my portable station, an 18" offset DSS dish. The response on the right of Figure 8 is the dual-patch feed. This patch feed is inexplicably 400 MHz low and has an obviously pitiful response. The patches are exactly the same size, so the author's assumption is the crude "through the hole" method of feeding the S-band patch through the L-band patch may be the culprit. The search for a "better" feed method for the inconvenient placement of the S-band patch led to a novel idea: using a piece of semi-rigid coax (0.141 dia.) for the feed. I just happened to have some of this handy with SMA connectors on both end. Using the semi-rigid coax and an SMA-to-N adapter worked well. **129**
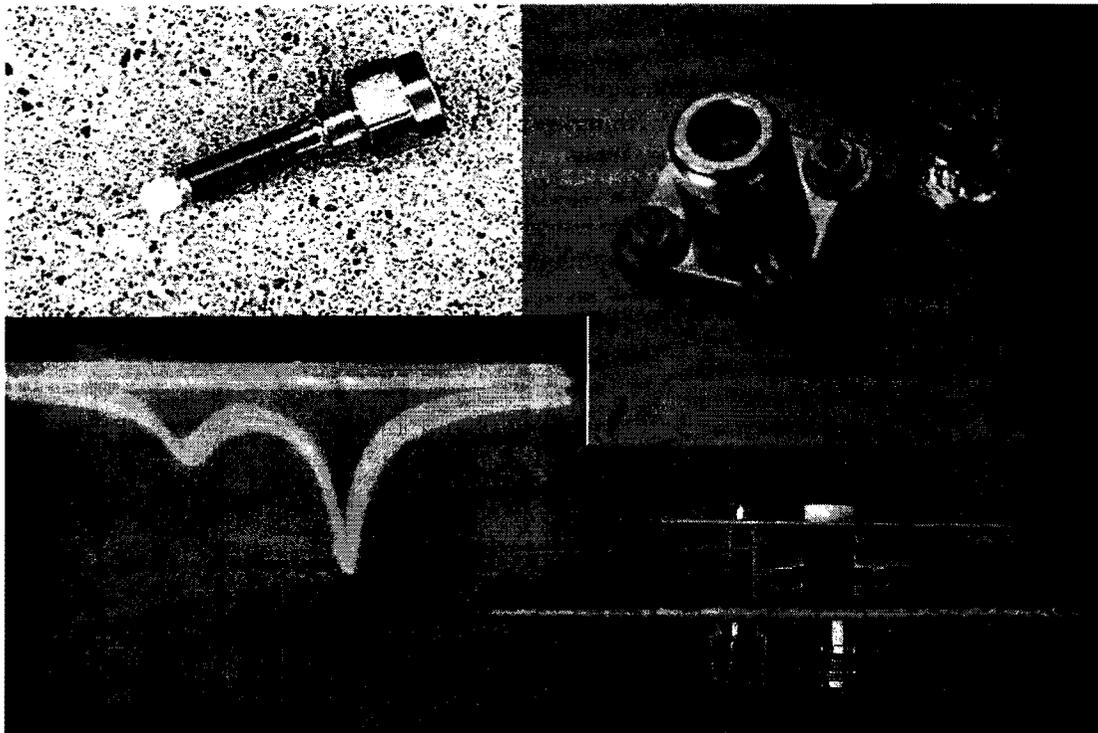
Figure 9 - The Semi-Rigid Coax w/SMA Connector Applied to S-band Patch

As can be seen above, the new feed method employing the semi-rigid coax worked well, with an almost 30 dB return loss. Note also in the figure above the use of a nylon bolt and nuts. In the next version I wanted to make some modifications, including rotating the S-band element 90 degrees to the L-band and trying metal hardware. The theory is, and several successful designs employ, grounding at the center of the patch--reducing static build-up and providing a more rugged design. I failed completely at getting this concept to work. The L-band was unaffected by a stainless steel bolt in the center (slight shift of resonance, but no change in return loss). Likewise, a lone S-band patch showed no perceptible (measurable) change with a metallic center support. The dual-band model, however, was a very different story. I built several models and tested them on two different spectrum analyzers (AG5RS and K5GNA, thanks) and could not eliminate the coupling of the S-band patch to the L-band patch. L-band was still unaffected, but the S-band showed a better response at 1300 MHz than at 2400 MHz!
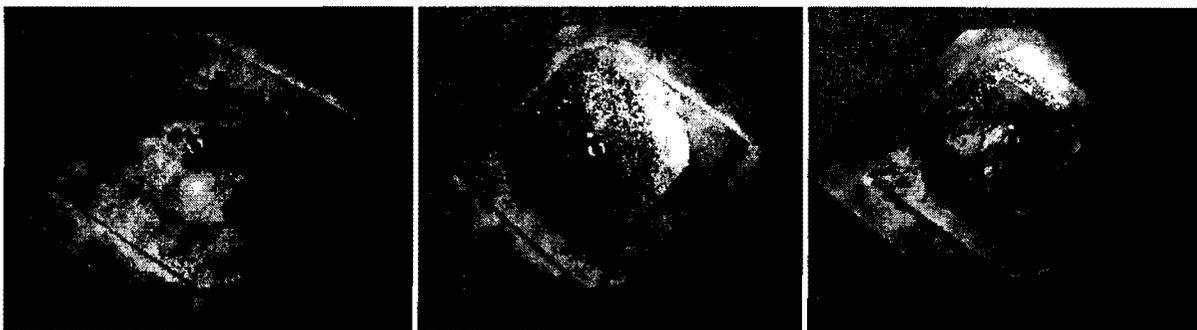

Figure 10 - Assembly of the Almost Final Version

The "almost final" version above was tested with the stainless hardware shown and had terrible S-band performance. Re-assembly with nylon hardware returned the feed to the level shown above in Figure 9. Several round patches, using an inverted brass screw and nut as a tuning/polarity capacitor were built, but I was unable to reproduce the success by W0LMD (18). I suspect the tolerances are tighter with this design and not having sophisticated machining tools nor convenient access to a spectrum analyzer, I failed to produce an L-band patch with the same low return loss.

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Other Dual-Band Antennas:

These are not the only dual-band antenna systems on AO-40. There are many varied, innovative designs available as further food for thought. Others have been found, including G6LVB, who constructed a simple and effective 1.2 m home-brew stressed "chicken wire" dish with a dual G3RUH helix feed (19). More appear every day as innovative ideas evolve into reality. As mentioned earlier, G3WDG has a 3 m dish with not only 13/23 cm helices, but a 1.3 cm feedhorn and W0LMD has interesting dual- and tri-band "soup can" patch feeds worthy of notice (20, 21). Finally, see the 5-band patch feed from ON6UG (22).

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A K-Band Receiver For AO-40
(For Less Than A King's Ransom)

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AO-40 was more than a decade in coming. Its long period of gestation gave us time to ponder the possibilities for upgrading to higher and higher bands. It always appeared to this author the "big gun" on AO-40 was going to be the X-band (10 GHz) downlink—a 50 Watt TWT feeding a high gain dish antenna. The catastrophe silencing the easy-to-hear 2 meter signal also, unfortunately, muted the X-band downlink. We were left with no "transition" microwave band to bridge us from the relatively plug-and-play world of S-band (2.4 GHz) operation to the realm of "real" microwaves. All, we were told, was not lost. We still had K-band (24 GHz) as a downlink. 24 GHz? 1.3 cm! Surely they were joking: before AO-40 I did not know we had a 24 GHz satellite band! K-band was the world of near-mm waves, of waveguides and horribly expensive components, and... of the unknown. So, with a mix of curiosity and apprehension, I went to the 2001 AMSAT-NA Symposium's "K-band breakfast" hosted by KC2HAX (1).
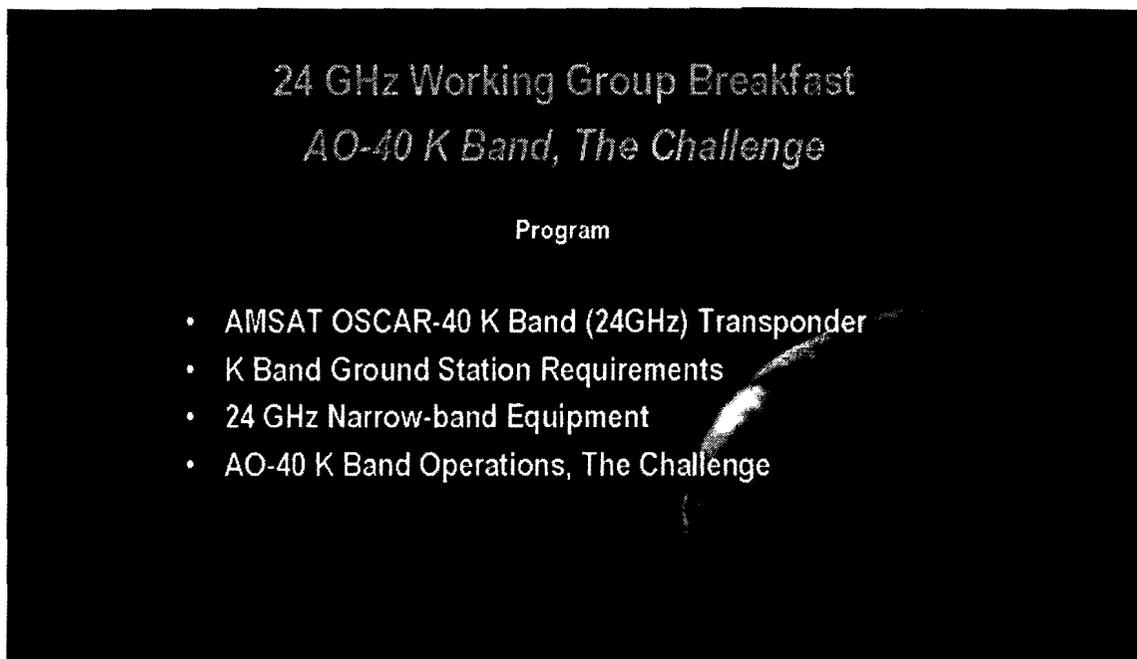

Figure 1 - The 2001 AMSAT-NA Presentation by AL7EB, KC2HAX, K5VH, and KD4APP

All my fears were confirmed: this was a multi-kilo-buck dream. The challenges were formidable, including daunting weather implications and esoteric groundstation design requirements. Clearly, this was a challenge for those "other guys."

Scroungers-R-Us
Well, maybe I learned just a little at that breakfast. The next thing I knew I was searching hamfests and ebay.com for things like waveguide filters, brick oscillators, and microwave relays. I was invited to a meeting of the Roadrunners Microwave Group (RMG) and joined (2). I asked smart people dumb questions. I carefully watched the progress of others, most notably G3WDG, OH2AUE, G6LVB, W5OE, and N1JEZ. While I was learning a little bit at a time, I was slowly collecting the odd parts and pieces to make up a 24 GHz system—just in case I "really" wanted to take on this challenge. Before I even realized it I had become a microwave experimenter!

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A Plan Was Taking Shape

One of the lessons I learned in playing with S-band gear over the last two years is the importance of being able to separate—to filter out—nearby strong signals such as local oscillator (LO) components in the output of a mixer and both internal and external signals at the *image frequency*. Some commercial K-band systems successfully use 144 MHz as an IF (3). I was afraid building and tuning a junk/surplus/hybrid system that "close" to the desired frequency was beyond my capabilities. After all, I don't even own any microwave test gear. At least not yet.

Concerns about strong LO products and image frequency proximity led me to follow a path I thought might be "safer" for a neophyte. I chose to use the now-comfortable 2,401 MHz as the first IF, allowing me to more easily filter out one side of the LO products and consequently placing the image frequency almost 5 GHz away from the desired frequency. A second benefit of this scheme is being able to use a filter wide enough to pass both the satellite band at 24,048 MHz and the terrestrial band at 24,192 MHz. A third, and significant benefit this scheme offers is using the 2,401 MHz first IF to hear the AO-40 S-band beacon in order to accurately point the antenna. This last benefit may prove to be the most noteworthy, as both N1JEZ and G6LVB tell me how very difficult it is to find the K-band signal in three-dimensional space.

Taking The Low Road

Starting with the received radio frequency (RF) of 24,048 MHz and an IF of 2,401 MHz, a simple mixer requires 21,647 MHz. The heart of the design is the mixer, a surplus P-com downconverter obtained from WB5TBL and documented by W5LUA (4). This particular downconverter has a built-in LO doubler circuit, ahead of the mixer, so an actual output of 10,823.500 MHz is required from the brick oscillator. The basic receiver frequency scheme is shown in Figure 2.
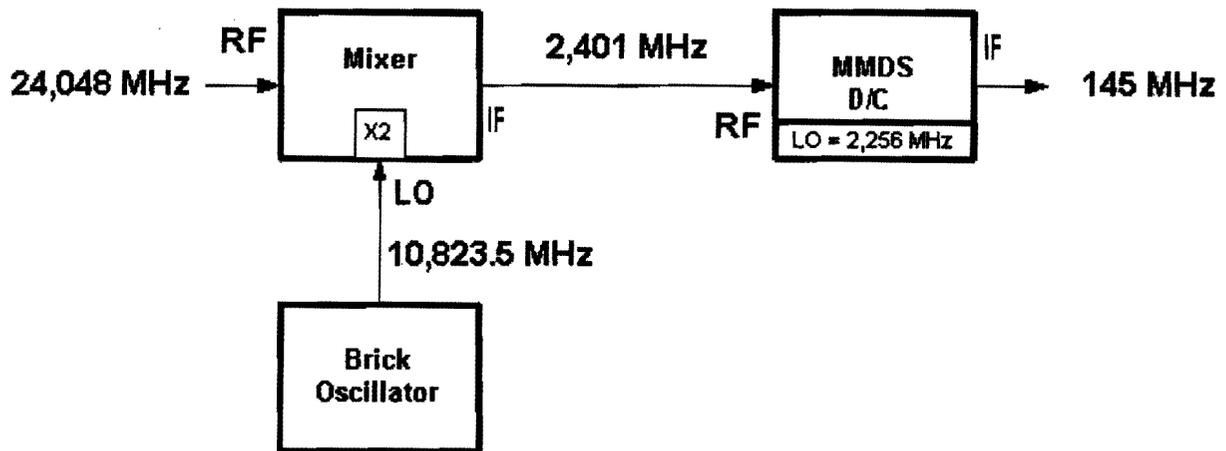

Figure 2 - Basic K-Band Receiver Scheme

Many of the design schemes popular for 10 GHz use high side injection of the LO. Using low-side injection, *i.e.*, the LO frequency is below the desired RF frequency, allowed me to keep the LO below 11 GHz and also avoids the confusion of an IF tuning in the reverse direction from the RF. As it turns out, finding surplus brick oscillators in the 13 GHz range required for high-side injection is considerably more difficult than finding 10 GHz oscillators.

First Laboratory Trials

The first order of business is setting the LO frequency. With the help of AG5RS and his well-equipped RF "laboratory," we set the surplus brick oscillator at 10,823.500 MHz. Then we arranged a P-com upconverter and downconverter pair to face each other across a 6" (150 mm) air

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gap and injected a test signal into the upconverter's IF port. We were stunned when we immediately heard the signal in the 145 MHz IF receiver (my trusty FT-100). AG5RS used his hand to block the 6" air gap to verify we were actually hearing the K-band signal and not an IF image or noise (both up and downconverters used 2401 MHz as an IF). Figure 2 shows the crude, but ultimately effective, test setup.
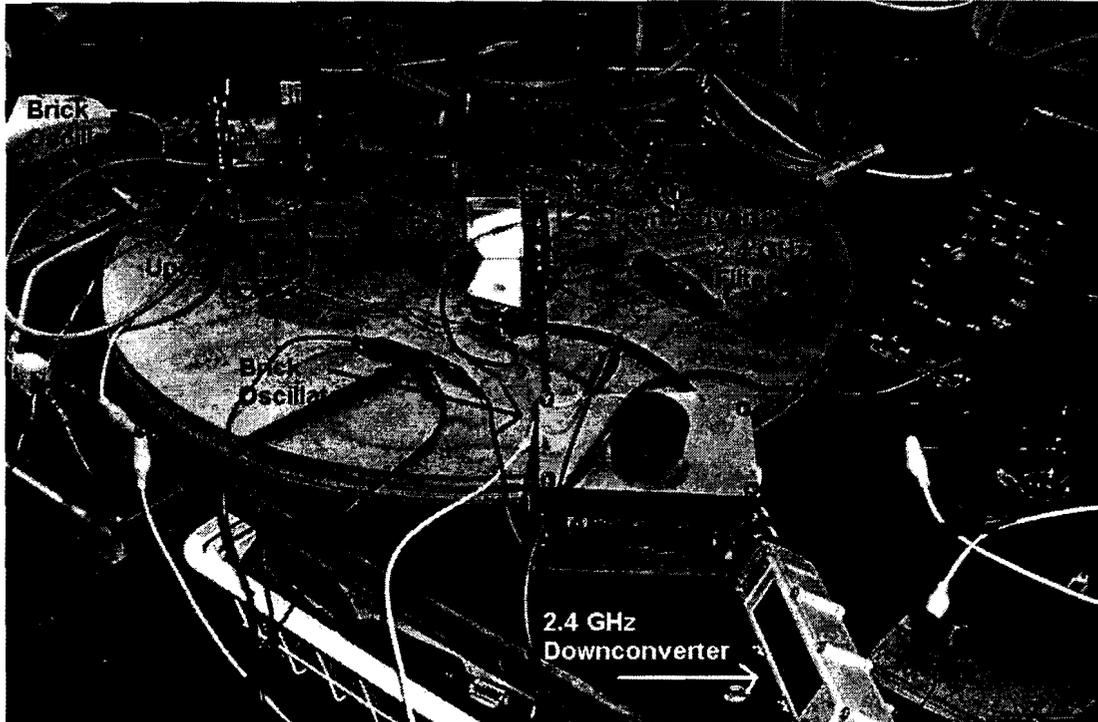

Figure 3 - Initial K-Band Test Setup at AG5RS Was Messy But Successful

I waited until this first critical test was completed before taking the next steps: buying a DB6NT preamp and designing and building a portable "rover" type setup. The new preamp was a bigger investment than the total of everything I had spent so far, but it was a critical component to achieve the needed NF and gain. For the adventurous, W5LUA has an inexpensive home-brew design you may want to tackle (5). Following the successful laboratory trials, the receiver design matured to the one shown schematically in Figure 4 and in mock assembly in Figure 5.

2.4 GHz Signal
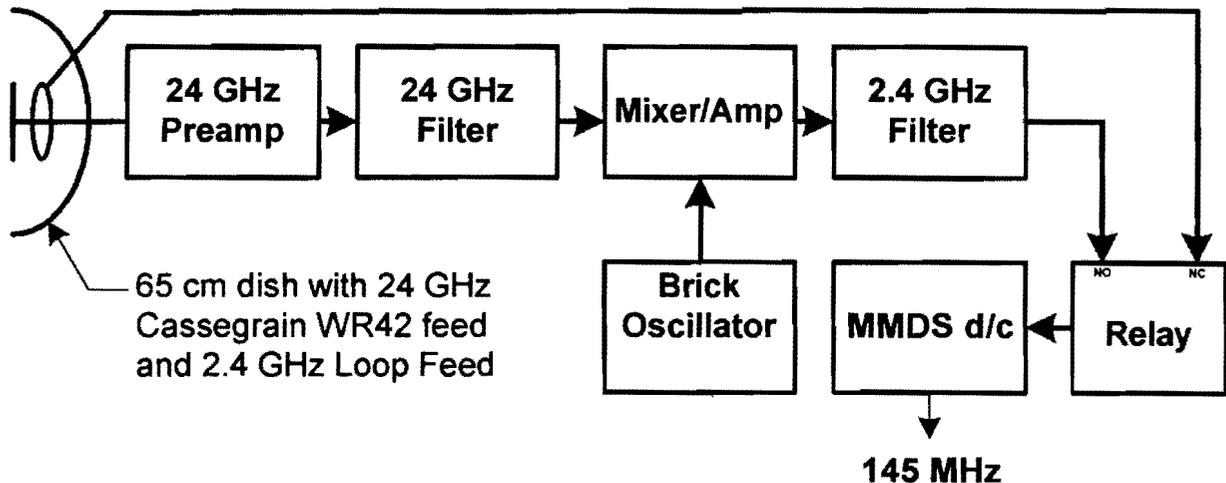
Figure 4 - Final K-Band Receiver Design
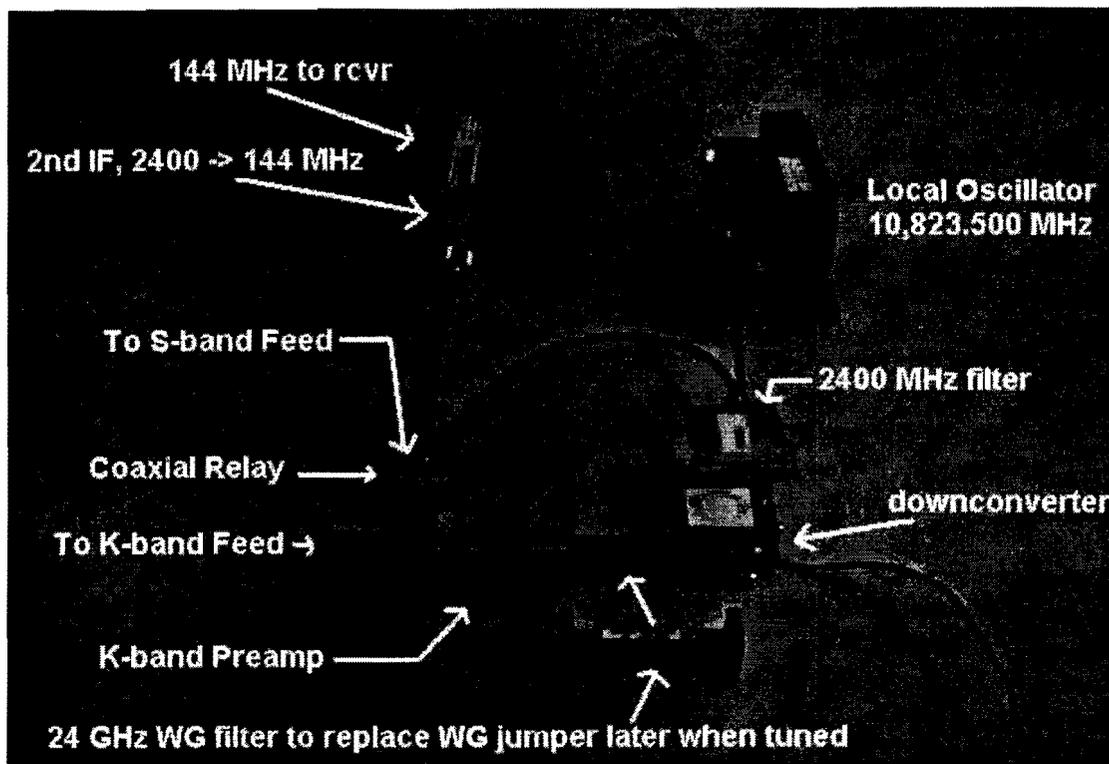
Figure 5 - The K-Band Parts In Mock Assembly

Where's The Signal?

I realized finding the K-band downlink
within a degree or two was going to be
difficult and was designing a system with an
inherent S-band receive capability. This is a
nice concept, but, I had not really addressed
how this would be accomplished on the
antenna hardware end. I had envisioned a
dual-band patch feed on an 18" DSS dish;
using the techniques developed for 13/23 cm
dual feeds (6). I had recently seen W5OE's
10/24 GHz system on just such a dish, albeit
using a more conventional feed horn and
waveguide assembly. Then I found a surplus
2' Andrew 23 GHz prime focus dish on
ebay—a change in the plan. I had also
recently seen K5VH's 2.3/10 GHz antenna
using a conventional 10 GHz splash feed and
a 2.3 GHz loop feed (7). I built a full-wave
loop as the 2.401 GHz feed element, placing
it one-half wavelength in front of the K-band
Cassegrain reflector. Much like a 2-element
beam, the feedpoint impedance is close to 50
Ohms. The loop presents minimal blockage
of the K-band feed and is routed out of the
antenna via a piece of semi-rigid coax and a
bulkhead SMA connector.
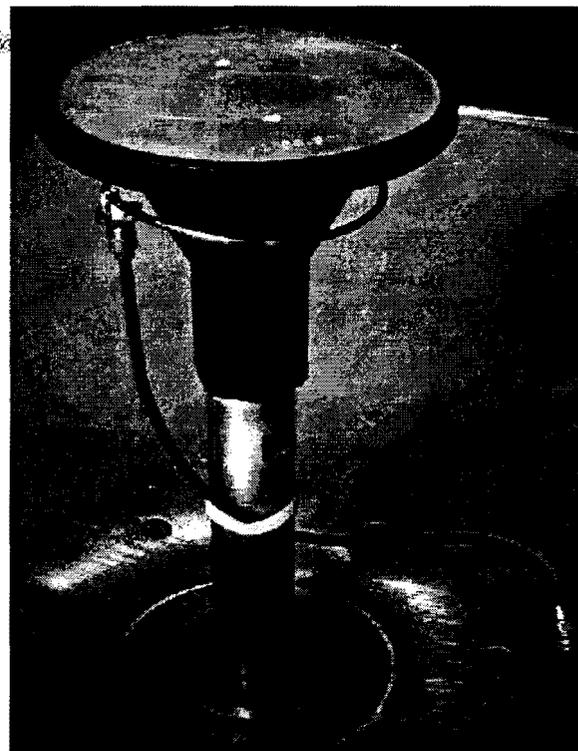
Figure 6 - S-band Loop Feed In Front of K-Band Feed

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Power Supply

Several voltage levels are required to put this hodge-podge of parts together in working fashion. At least 16 Vdc was needed for the MMDS downconverter and the 28 Vdc-rated SMA relay. 12 Vdc was needed for the P-com mixer and the DB6NT preamp. The Frequency West brick oscillator utilized –20 Vdc. Finally, to convert the system to terrestrial work later, I would also need –5 Vdc for the matching P-com upconverter.

I searched and searched for a suitable power supply and found none really suited for this collection of Voltages. Personal computer switching power supplies have most of these voltages, but require serious surgery to coax the –12 Vdc to the required –20 Vdc. In a hurry to get the system together for further testing, I quickly designed a simple linear circuit using some spare "wall wart" power cubes I recently bought on ebay for $0.99. These units are rated 12 Vdc at 800 mA (unloaded), but tested at over 18 Vdc. Since my initial tests were successfully made with only –16 Vdc, I decided to give it a try.
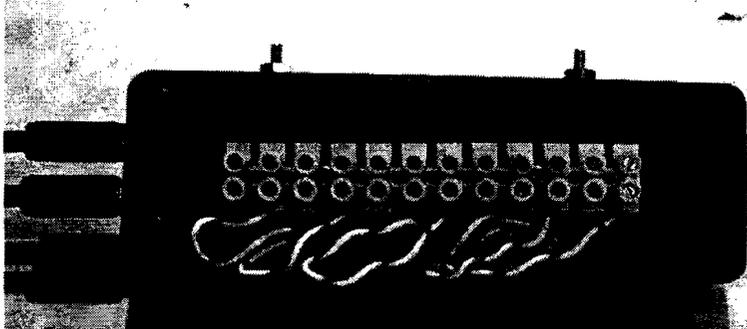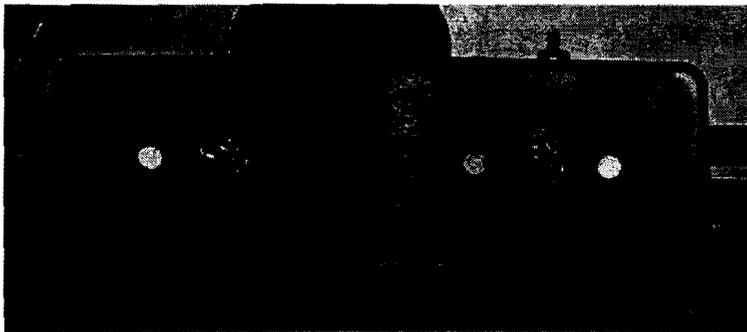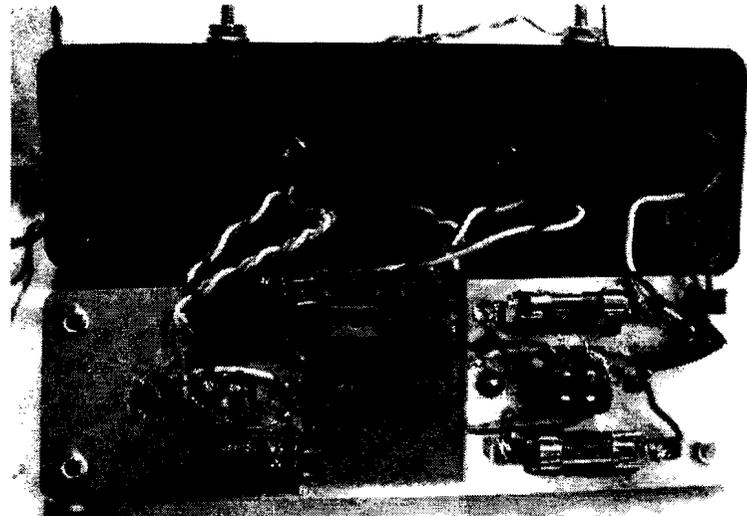
Figure 7 - Linear Power Supply Construction: Internals, Front, Rear

The circuit uses a 7812 for the +12 Vdc, a 7905 for the –5 Vdc, and the +18 and –18 Vdc float on the power cube output. The power supply is constructed using simple point-to-point wiring, is contained within a 5x15 cm enclosure with terminals on the back for connecting the various receiver components, and has a pair of 1/8" jacks for connection of +/- 18 Vdc from the outboard power cubes. The two LEDs on the right are used for verifying status of the + and – power busses, and the switch and LEDs on the left are for the S/K relay. After completing the power supply and powering all the components, however, the –18.5 Vdc circuit drooped to –14.5 Vdc as the brick oscillator drew over 350 mA. Testing of the oscillator showed it would operate at the reduced Voltage, but the output of the oscillator was also reduced from the specified 11 dBm to 7 dBm. This was a minor setback, but I searched around the junk box and found a small power supply to substitute for the negative supply cube while I continue the search for power cubes with a little more "oomph." This modular design allows any external sources of +/- 20 Vdc to be used.

Integration and Calibration

The next step was to integrate all the components in a close-coupled physical arrangement behind the dish. N1JEZ's crafty setup provided the inspiration for the almost-ready setup shown below (8). Obviously, the system is set up like a "rover," and not for fixed ground station operation. It is also a fair-weather design. The common hardware peg board is quite handy for bolting and tie-wrapping the components in place as well as for routing the power cables through to each device; ending up with quite a neat arrangement (on top of the board, anyway).
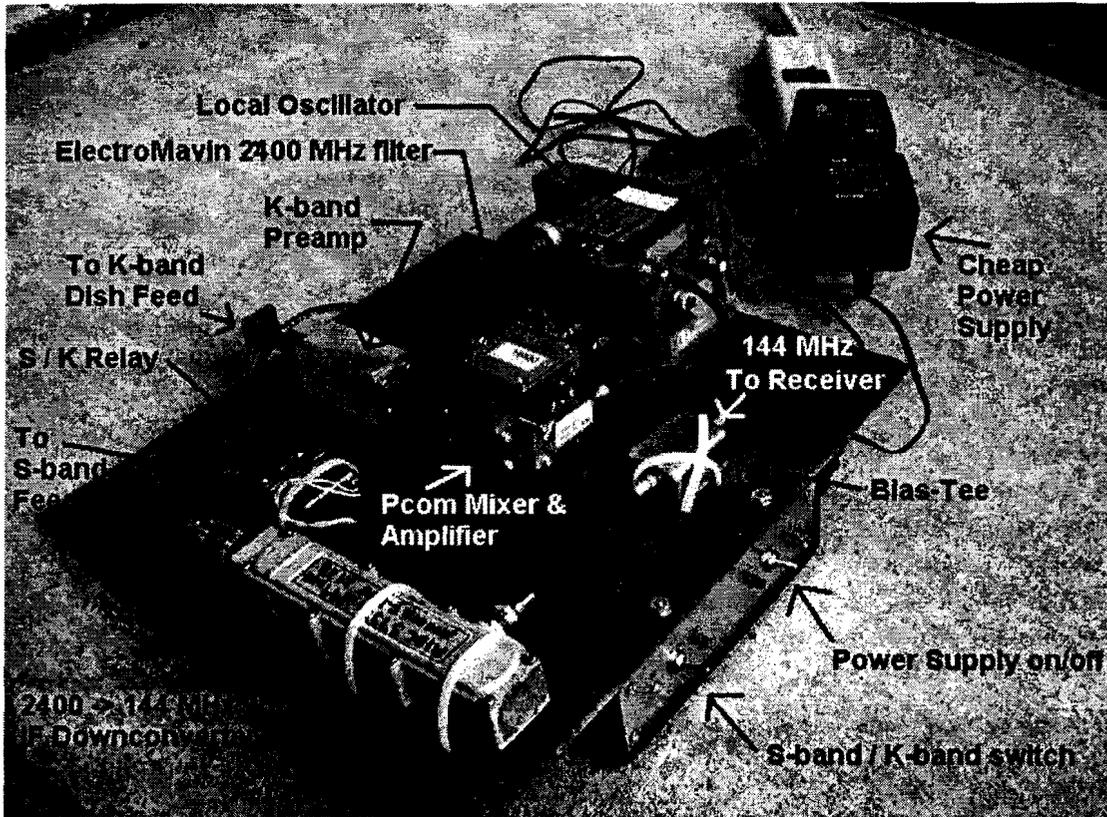

Figure 8 - The Completed K-band System Ready for Testing

Fate:

I was all ready to go. The very next weekend looked like a perfect opportunity for my first attempt at hearing the AO-40 K-band beacon: good windows for North America on both Saturday and Sunday. Then, on 16-July-2002, the unexpected happened...

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***AO-40 UPDATE***

The K-Tx sessions have been discontinued due to increasing solar
angle.   We will post more detailed plans for the upcoming bad solar
alignment shortly….

QST AO-40  S2 Downlink      #=Wednesday only      2002-07-16
          MA       036   120#  128   160   200   240   036
          --------1-----4-----3-----5-----7-----0-----1
          MB      |  *  |  *  |     |  *  |  *  |  *  |   |
          RUDAK   |     |     |  *  |     |     |     |   |
          V-Rx    |     |  *  |  *  |     |     |  *  |   |
          U-Rx    |  *  |     |     |  *  |  *  |     |   |
          Passband | UL | VL  |     | UL2 |     |     |   |

--W4SM for the AO-40 Command Team
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Figure 9 - The AO-40 Command Team Message from W4SM

The curtailment of K-band operation on AO-40 was disappointing, but it also gave me a little more time to work on the system. I made the trek out to K5GNA's shop to put the integrated system on his HP analyzer. We generated a signal at 12 GHz and looked for the harmonic at 24 GHz. We were rewarded with a huge signal visible in the 2nd IF's VHF output, as shown in Figure 10. The overall system measured 54 dB of gain.
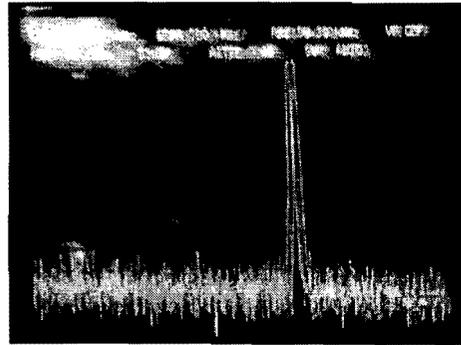

Figure 10 - Signal at 24 GHz

I subsequently took the equipment home and set up my own trial using more modest "test" gear. To generate a test signal at 24 GHz, I employed my GM1SXX-designed "duckling" S-band marker oscillator at 2401.500 MHz with the "antenna" generating weak harmonics of the Drake's LO and close-coupled to the waveguide input to the receiver's preamp (9, 10). The "signal detector" used was my FT-100. Finding the signal on the 2nd IF's VHF output was not difficult, but the warm-up drift of the MMDS oscillator was significant once multiplied 10 times! A temperature-stabilized S-band oscillator would make a good tool to have around the shop.

Terrestrial Trial
With AO-40's K-band transponder temporarily off, I opted to do a mock test using the complete system and testing the S/K switching function. The satellite was around MA=220 with a range of 30,000 km and a squint of 15 degrees. It was a simple task to manually point the antenna and find the S-band downlink. I was unsure what to expect from the unproven loop feed, but was grateful to see the signal at 5 S-units above the noise on my FT-100 (about equal to what I receive on an 18" DSS dish with patch feed). That proved the S-band half of the setup works to expectations.
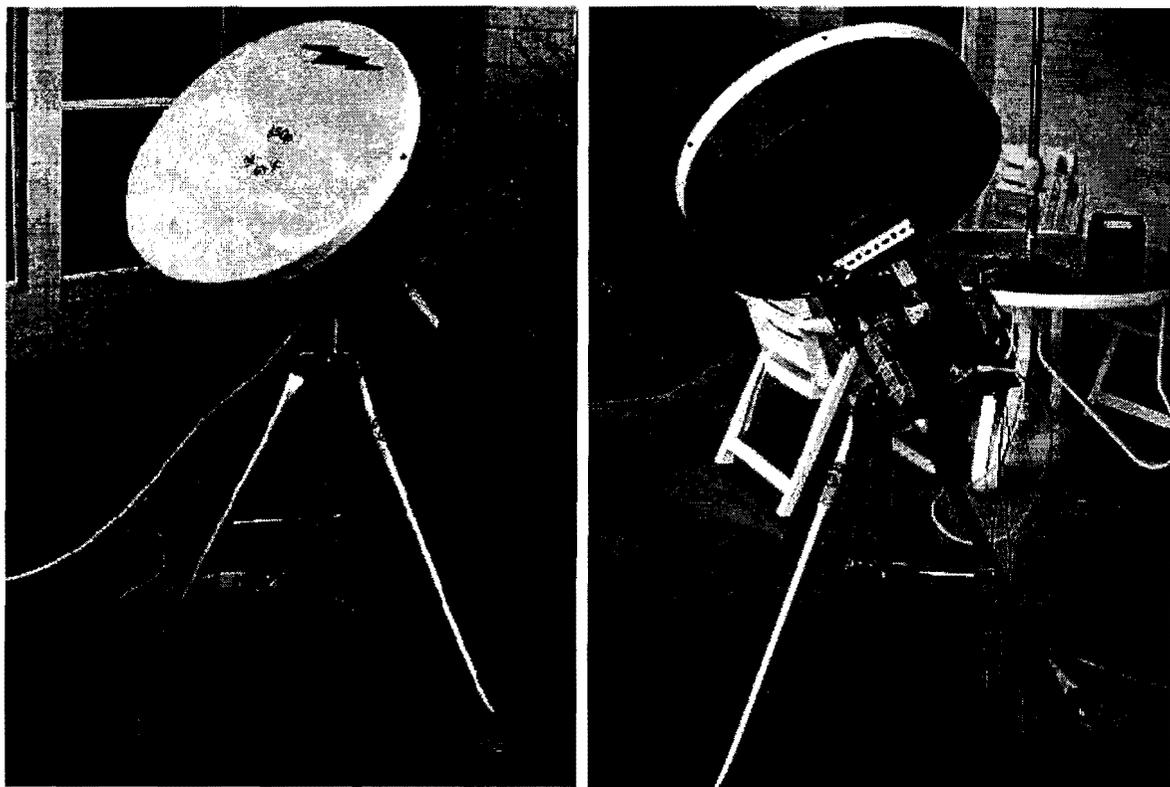

Figure 11 - Completed Dish and Receiver Set Up for Real S-band and Simulated K-band Operation

To complete the K-band simulation, I then set my mock-AO-40-K-band-signal on top of the patio table—the 2401.500 MHz signal source. The 10th harmonic is at 24,015 MHz. I then rotated the antenna and quickly found the signal with an S9+20 dB reading on my FT-100. I completed the simulation by rotating the antenna in azimuth and confirming I could "lose" the signal. It was a good simulation and I feel I am ready for AO-40 now. I look forward to the K-band downlink's return in the fall/winter of 2002/03.

As of writing this I have yet to hear the AO-40 satellite downlink on K-band, but I have learned a significant amount in this venture. With the exception of the DB6NT preamp, this system is not much more expensive to home brew than one for S-band. I have not spent a "king's ransom" and feel like I got a solid introductory education in microwaves just by taking the plunge. Many people came forward to help me: I could not have done it on my own. I still have much to read to better comprehend microwaves and microwave construction, but I certainly know more today than I did last fall when I went to the K-band breakfast. Finally, one bit of advice I offer from my experience is to either 1) acquire the test gear first or 2) line up somebody who has the appropriate equipment and can help you. You won't get far without it.

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